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Investigation on equinoctial asymmetry observed in Niamey Station Center for Orbit Determination in Europe Total Electron Content (CODG TEC) variation during ~ solar cycle 23

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This is an investigation of equinoctial asymmetry in Total electron content (TEC) variability at Niamey (Latitude: 13° 30' 49.18" N, Longitude: 2° 06' 35.28" E) using the Global Ionospheric Maps model constructed by the Center for Orbit Determination in Europe (CODG model) during solar cycle 23, that is, from year 1999 to year 2009. Niamey Center for Orbit Determination in Europe Total Electron Content (CODG TEC) from 1999 to 2009 show that ionization follows solar cycle and presents semi-annual variation with equinoctial asymmetry. In CODG TEC, generally, March/April maximum density is larger than that of September/October except during years 1999 and 2001. For all years (1999-2008), electronic density is higher between 1400 and 1700 UTC with the maximum at 1400 UTC. On one hand, Ap and aa index via pixel diagram and on the other hand, seasonal and sunspot cycle variation have been used to explain the exception of years 1999 and 2001. It was found that asymmetry of 1999 is due to solar wind particularly to fluctuating wind and asymmetry of 2001 results from CMEs.

Key words: Global positioning system (GPS), Center for Orbit Determination in Europe Total Electron Content (CODG TEC), ionization, asymmetry, equatorial ionosphere.

INTRODUCTION

The equinoctial asymmetry in monthly or seasonal ionospheric parameters such as foF2, NmF2, TEC (Rishbeth et al., 2000; Chakraborty and Hajra, 2008; Ouattara et al., 2012; Naněma and Ouattara, 2013; Hajra et al., 2016) and in geomagnetic activity (Green, 1984; Cliver et al., 2000; 2002; Chakraborty and Hajra, 2010; Hajra et al., 2013) have been intensively investigated and three principal hypotheses or mechanisms are proposed

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to explain such variation: (1) axial mechanism (Bohlin, 1977) for which the peak occurrence times correspond to those of the maximum of solar B_0 angle (Cliver et al., 2000). This mechanism is also explained by seasonal variation of solar wind speed (Murayama, 1974); (2) equinoctial mechanism (Svalgaard, 1977) where the peak occurrence times are those of the minima of the solar declination (Cliver et al., 2000 and (3) Russell-McPherron mechanism (Russell and McPherron, 1973) where the peak occurrences are due to those of the maximum of solar P angle. The solar B_0 angle corresponds to Earth's heliographic latitude; and the solar P angle is the position angle of the northern extremity of the Sun's rotation axis, measured eastward from the north point of the disk (Cliver et al., 2002).

For the understanding of the response of CODG model in West Africa region, we morphologically analyse CODG TEC time variation from 1999 to 2009 as a function of sunspot number R12. Pixel diagrams were also built with geomagnetic aa and Ap indices. The three mechanisms (Axial, Russell McPherron and equinoctial) were verified for explaining ionospheric semi-annual variation. One of the goals of the present paper is to determine a possible cause of the asymmetry.

MATERIALS AND METHODS

The Total Electron Content (TEC) at Niamey station (Geo Lat 13°28'45.3"N; Geo Long: 02°10'59.5"E) during solar cycle 23 was determined using the model of the coefficients of the ionosphere given by Centre for Orbit Determination in Europe (CODE). The CODE is one of the centres of analysis of International GNSS Service (IGS, http://www.igs.org/network). The Global Ionospheric Maps model constructed by the Center for Orbit Determination in Europe (GIM/CODE or CODG model) is used to get the Total Electron Content. Throughout the paper TEC obtained with the GIM/CODE model is called CODG TEC. The database includes:

(1) CODG TEC computed at Niamey station (Geo Lat 13°28'45.3"N; Geo Long: 02°10'59.5"E) in Niger by using IGS database where IGS means International GNSS (Global Navigation Satellite Systems) Service. These data can be found at http://igscb.jpl.nasa.gov;
(2) Geomagnetic index aa (Mayaud, 1968, 1971, 1972, 1973), taken from SPIDR database (http://isgi.unistra.fr/data_download.php), permits the evaluation of different geomagnetic conditions (quiet and disturbed conditions).
(3) Sunspot number R12 data provided by database http://www.sidc.be/silso/datafiles, gives the different solar cycle phases years.
(4) The planetary index Ap, obtained from NGDC database (http://www.ngdc.noaa.gov), characterizes the geoeffectivity of solar particles (Chapman and Bartels, 1940) from coronal holes (Nolte et al., 1976).

It is well known that there are three types of solar winds (Legrand and Simon, 1989; Simon and Legrand, 1989; Richardson et al., 2000; Richardson and Cane, 2002; Ouattara and Amory Mazaudier, 2009): (1) high stream solar wind speed coming from coronal holes; (2) slow solar wind coming from solar heliosheath and (3) fluctuating solar wind due to the fluctuation of solar neutral sheet.

It can be noted that:

(1) Ap index permits the evaluation of the impact of each type of solar wind (high solar wind speed, slow solar wind and fluctuating solar wind). In fact, this parameter is correlated to solar wind velocity (Snyder et al., 1963; Crooker et al., 1977; Ahluwalia et al., 1994); moreover, it gives a possibility to evaluate the response of the magnetosphere to solar wind inhomogeneity (Dessler and Fejer, 1963); Tsurutani et al. (1995, and references therein) pointed out that Alfvén waves are able to provoke geomagnetic disturbances in high latitudes via their southward magnetic field components. These disturbances are taken into account in the determination of Ap values (Ahluwalia, 2000). The other sources which contribute to the estimation of Ap values are coronal mass ejections (CMEs) (Gosling, 1976; Newkirk et al., 1981) which was first observed by using the coronagraph installed on board The Seventh Orbiting Solar Observatory (OSO-7 satellite) launched on 29 September 1971 (Ahluwalia, 2000).
(2) aa index permits the evaluation of different geomagnetic conditions (quiet and disturbed conditions) and particularly the determination of each class of activity by means of pixel diagrams (Ouattara and Amory-Mazaudier, 2009).

In the present paper, monthly CODG TEC are analysed with attention focused on equinoctial peaks and their asymmetry in order to determine its probable solar sources. This will be done not only by means of pixel diagrams but also by the use of Cliver et al. (2002) results.

RESULTS AND DISCUSSION

Here, the results and analysis were first presented followed by expose of the possible source the peak asymmetry. Figures 1, 2 and 3 give monthly CODG TEC variation from year 1999 to 2007 at Niamey Station. In the top of each panel, red colour shows Ap index monthly variation. In each panel, months are given in abscises axis and universal time calculate (UTC) in ordinates axis. In this figure, TEC is expressed in the unit of 10^{15} el/m^2 (TECU) and colour code starts from blue (corresponding to zero) to red (corresponding to 1400 TECU).

CODG TEC highlights semi-annual variation which is well known in ionosonde data monthly variation. It can be seen in Figures 1, 2 and 3 that the equinoctial maxima and its asymmetry; in general, the maxima of October are superior to those of March except in 1999 and 2001 where it is opposite. Ionization is maximal between 1200 UTC and 1700 UTC with its maximum density at 1400 UTC for all panels. Moreover, it can be noted that on one hand, the intensity of the equinoctial maxima varies with solar cycle (R12) and on the other hand, TEC intensity is correlated with the Ap value.

Figure 4 shows monthly TEC (red) and monthly R12 (blue) evolution from 2000 to 2010 which shows that annual TEC varies with sunspot number; in consequence, annual electronic density can be expressed as a function of sunspot number.

Figure 5 shows season variation of CODG TEC during quiet time characterized by days where aa ≤ 20 nT (panel a) and during disturbed period characterized by aa > 20 nT (panel b). This figure exhibits that the highest peaks appear during solar maximum. This result is consistent with the ionosonde data of Ouagadougou Station as

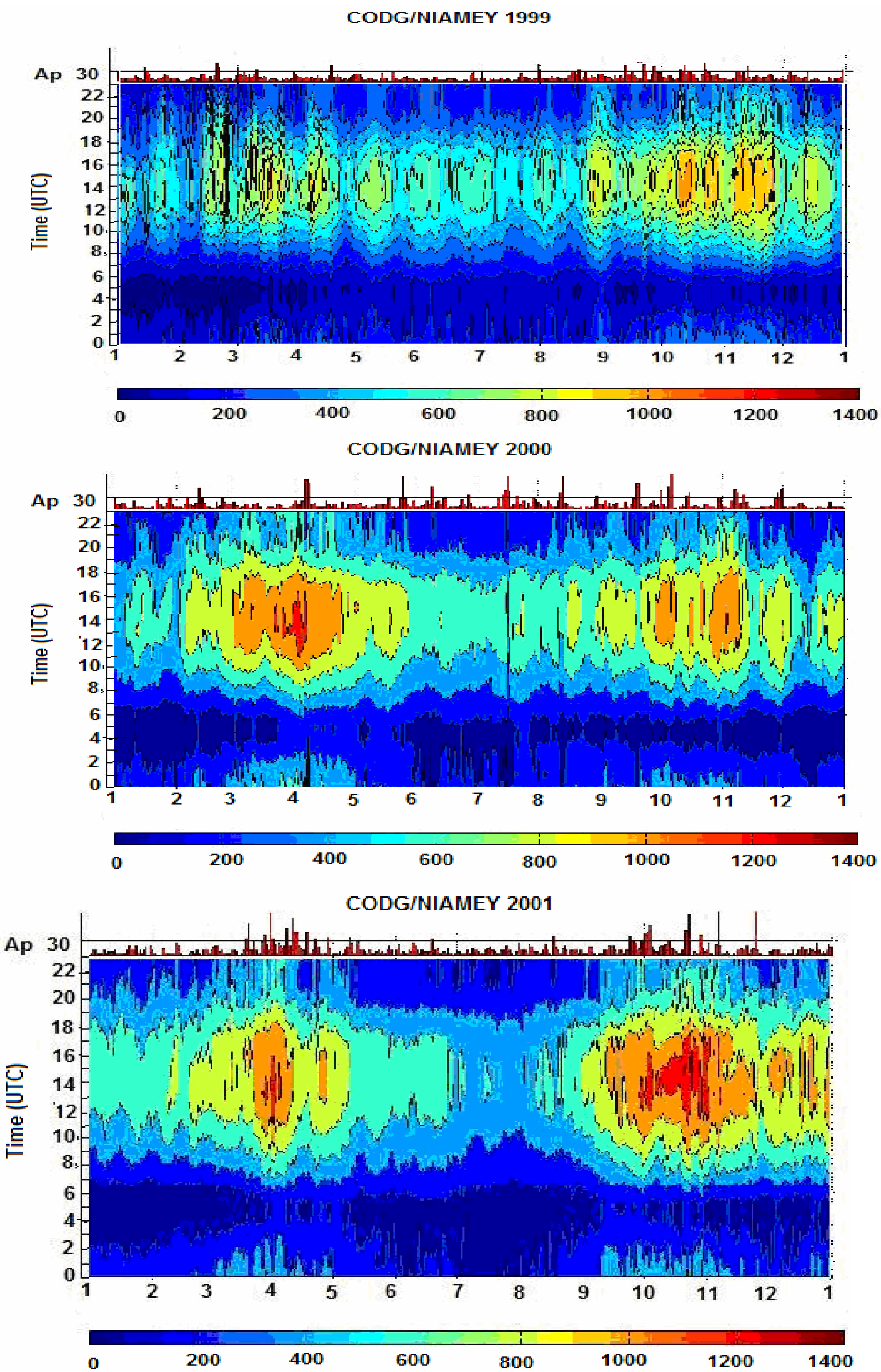

Figure 1. Diurnal CODG TEC evolution from 1999 to 2001.

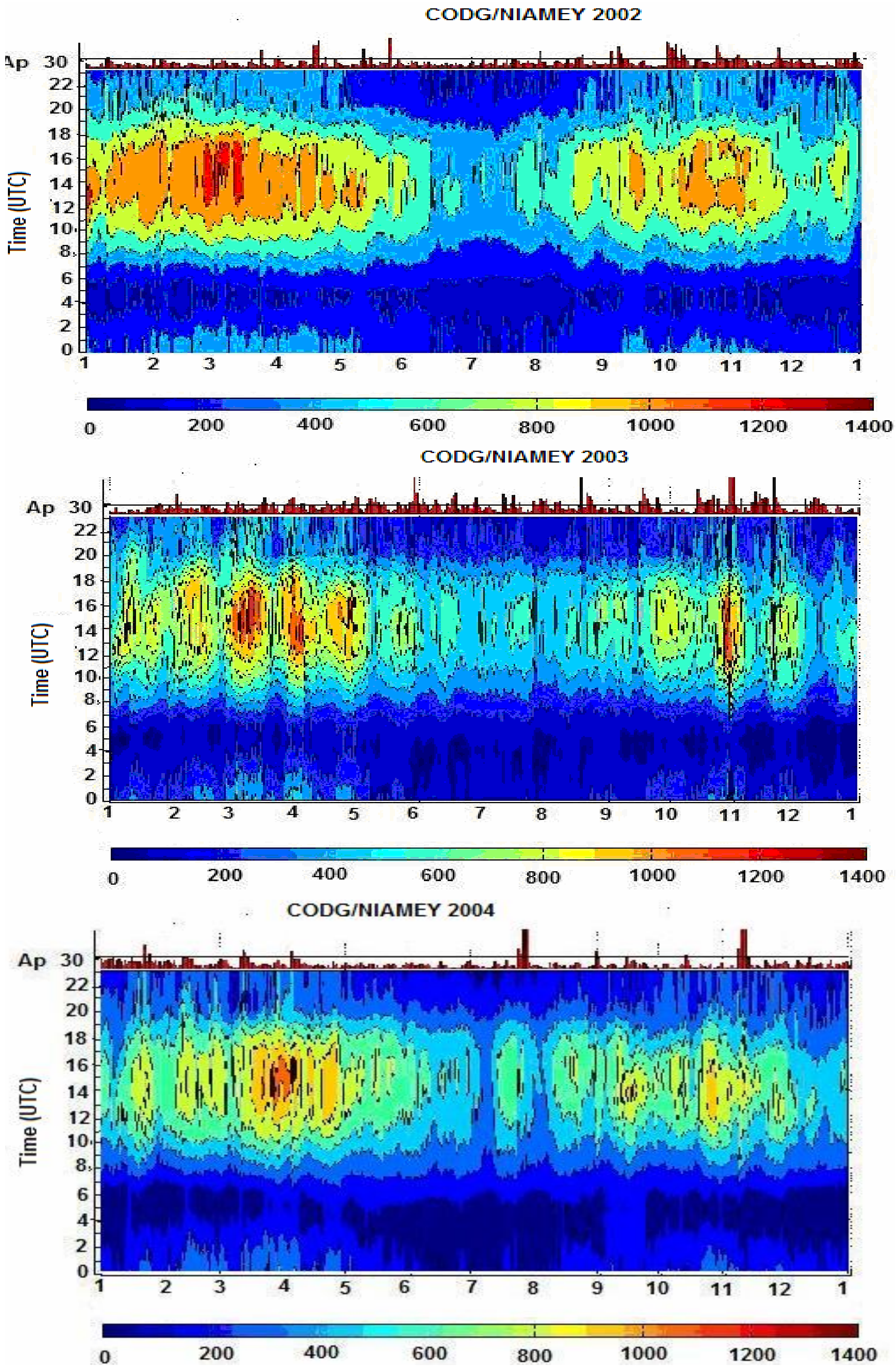

Figure 2. Diurnal CODG TEC evolution from 2002 to 2004.

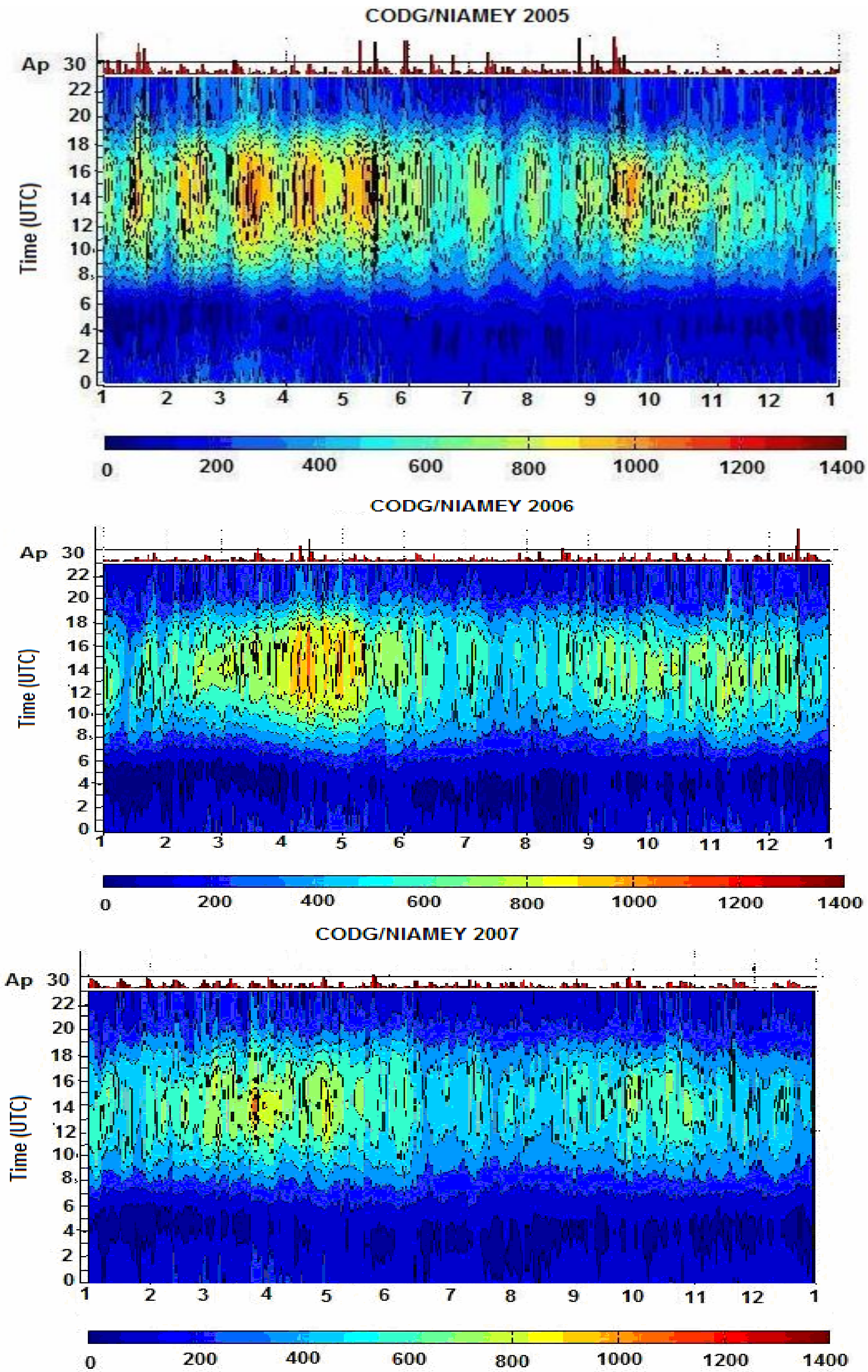

Figure 3. Diurnal CODG TEC evolution from 2005 to 2007.

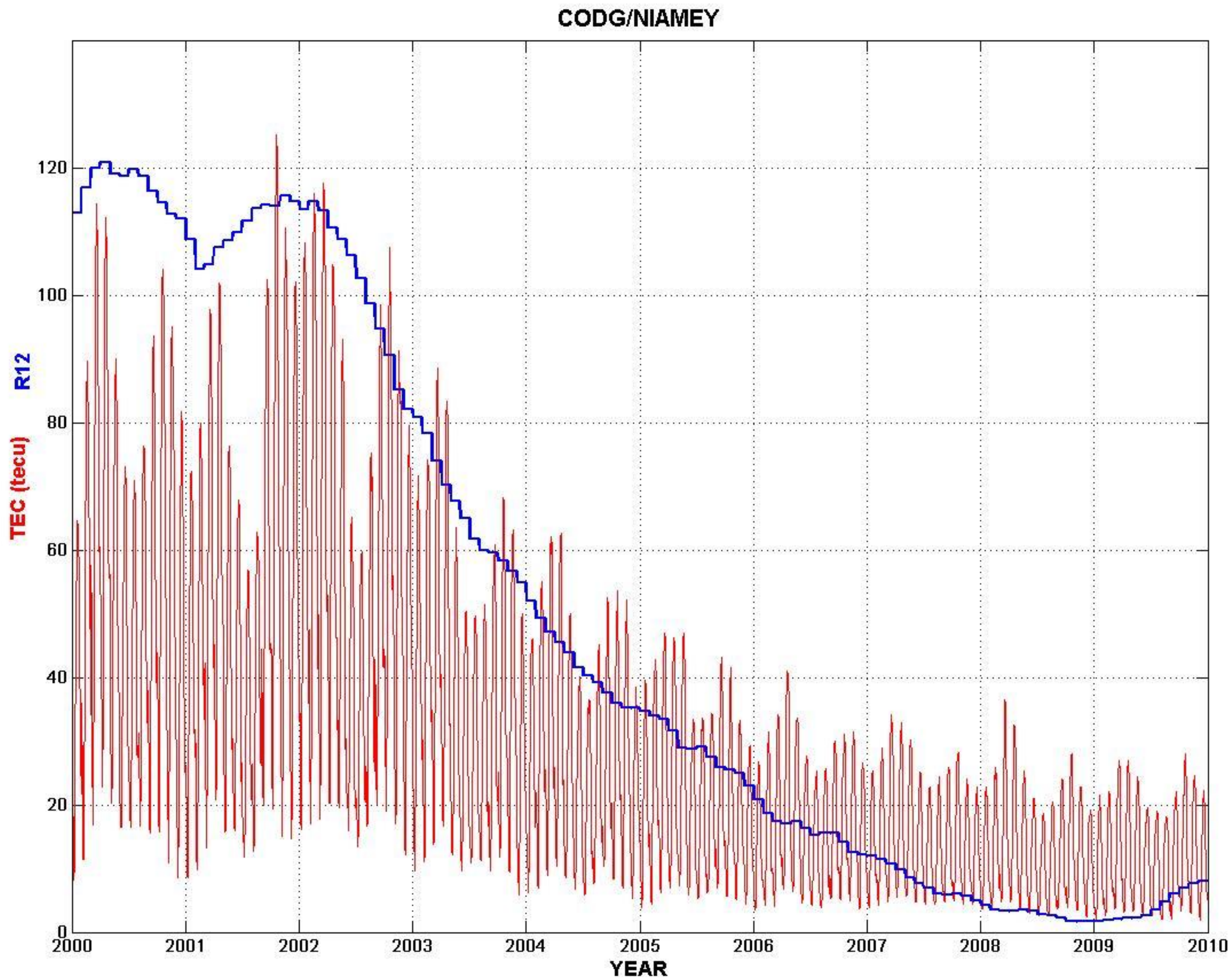

Figure 4. Monthly CODG TEC and R12 variation from 1999 to 2010.

reported by Ouattara et al. (2009). In panel a, one can see the peak asymmetry and March/April peak is higher than that of September/October for all years except these of 1999 and 2001 where it is the opposite. The comparison between results of panels a and b shows that peak amplitude is higher during disturbed period than that of quiet period and the disturbed condition does not modify the asymmetry observed during quiet time.

Analyses of these TEC variations will allow us appreciate (1) the annual variation of the ionosphere and the effect of solar phases on the ionosphere and (2) the impact of solar events on ionosphere.

Possible sources of CODG TEC seasonal asymmetry

To determine the source of CODG TEC asymmetry, sunspot number R12, geomagnetic Ap index, pixel diagrams and the results of Cliver et al. (2002) were used.

a) CODG TEC asymmetry source according to sunspot number

Figure 6 gives seasonal TEC variation at 1200 UT as a function of sunspot number R12 from 1999 to 2008. The green graph concerns local summer season (July month); blue graph is devoted to spring season (March/April); and pink graph highlights autumn season (September/October) TEC variations. Chestnut graph gives winter season (January) TEC variations. Each graph symbol corresponds to one year. From bottom to up, year increases from 1998 to 2007.

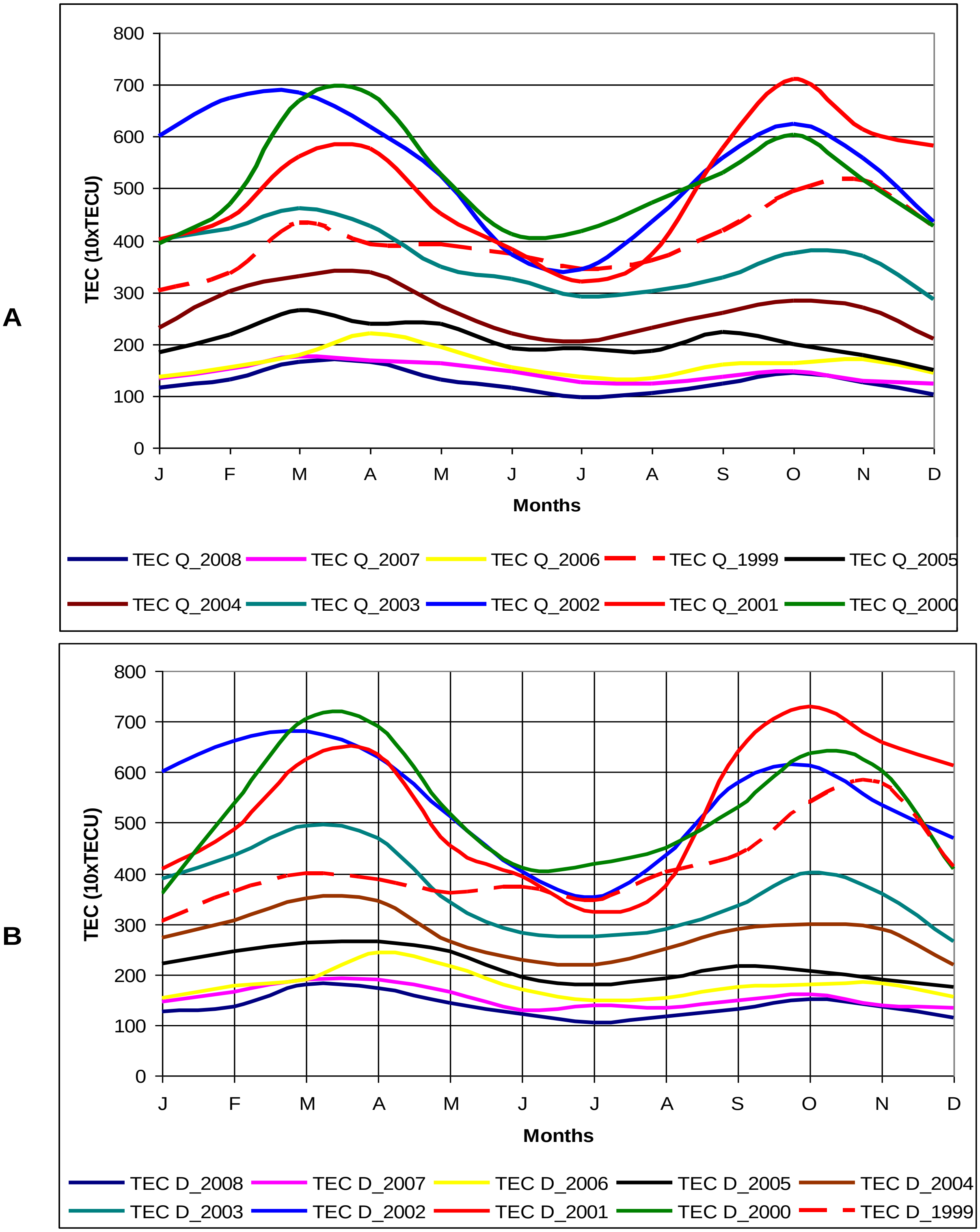

Figure 5. Seasonal CODG TEC variation from 1999 to 2008 during (panel a) quiet days and (panel b) disturbed days.

From Figure 6 it can be concluded that there is linear dependency between seasonal TEC and sunspot number R12. When R12 is less than 96, TEC increases linearly with R12 and the correlation coefficient is in range [0.924, 0.984]. For a given sunspot number, July TEC is the largest than the others. The analysis of Figure 6 exhibits

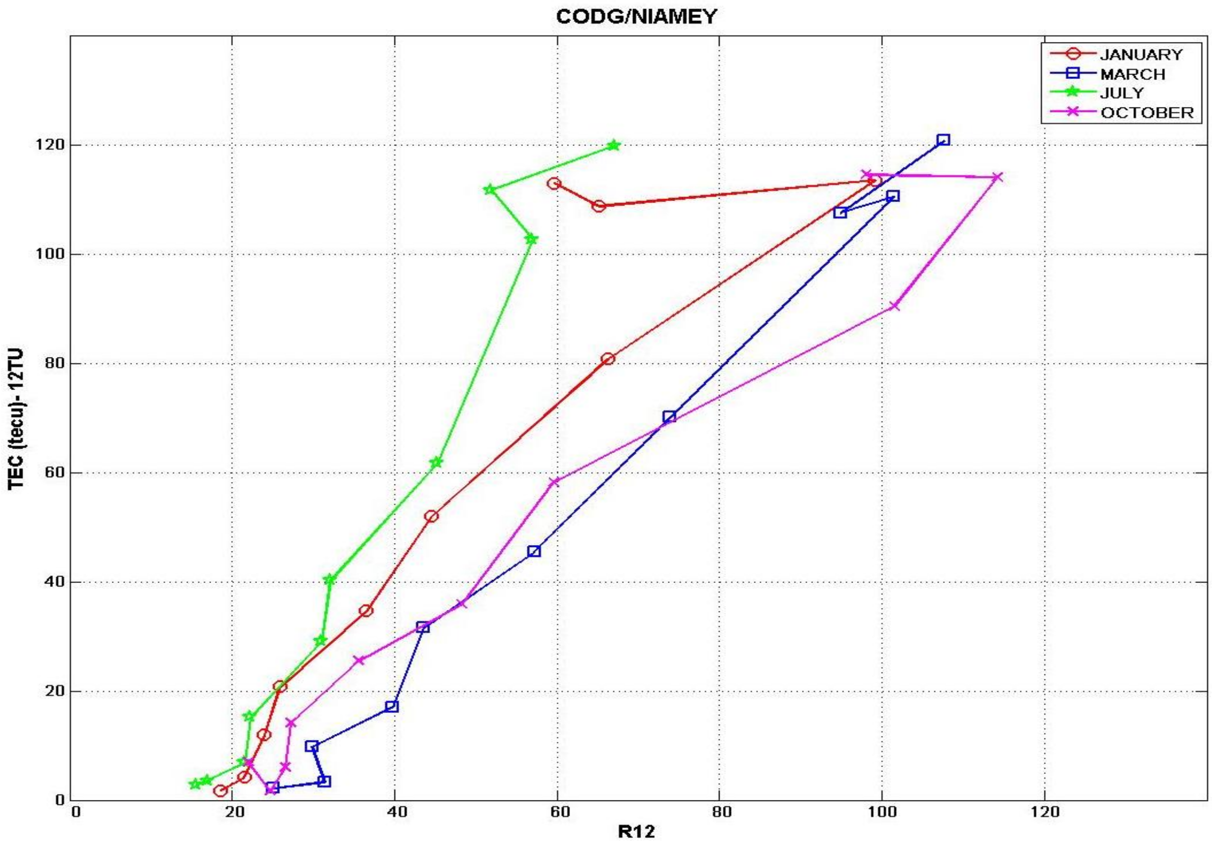

Figure 6. Seasonal CODG TEC variation as a function of sunspot number.

that (1) CODG TEC increases linearly with sunspot number until CODEG TEC is less than 100 TECU, (2) CODG TEC does not show winter anomaly because summer CODG TEC is always larger than that of winter and (3) for R12 = 42, R12 = 76 and R12 = 102 there is no equinoctial asymmetry. For R12 < 42 and 42 < R12< 76, October ionization is larger than that of March and for 76 < R12 < 116 it is the opposite. If only the equinoctial asymmetry results from sunspot, we do have four years (1999, 2000, 2001, 2002) with equinoctial asymmetry anomaly (with respect to the other asymmetry observed during 2003 - 2009) but according to Figures 1, 2 and 3 only two years (1999, 2001) CODG TEC have equinoctial asymmetry anomaly; therefore, we must assert that sunspot is not the only one responsible of such anomaly. To determine the other sources of equinoctial asymmetry anomaly observed during years 1999 and 2001, this research will investigate two ways: (1) utilization of Ap index and (2) employment of pixel diagrams.

We used the planetary index Ap by considering its characteristics notified previously. Pixel diagrams are utilized for permitting the evaluation of the action of different solar events (slow solar wind, solar wind stream, fluctuating solar wind and CMEs) (Legrand and Simon, 1989; Simon and Legrand, 1989; Ouattara, 2009; Ouattara and Amory Mazaudier, 2009).

b) CODG TEC asymmetry source according to Ap index values

Figure 7 presents the two-dimensional monthly CODG TEC variation for year 1999 (Panel a) and year 2001 (Panel b). In year 1999 (Figure 7a) it can be seen that that there is correlation between Ap and CODG TEC during September/October equinox while it is not the same during March/April equinox. Thus, this asymmetry may be due to solar wind by reference of the correlation between Ap index and solar wind as previously indicated. In year 2001 (Figure 7b), the maximum of Ap amplitude arrives at the same time with CODG TEC maximum value during March/April equinox. This situation is not observed during September/October equinox. Therefore, it can be concluded that there is no correlation between Ap and CODG TEC during September/October equinox, whereas the correlation is observed between these two parameters during March/April equinox. Thus, the equinoctial asymmetry observed is not due to solar wind. By reference to parameters which contribute to Ap (as previously indicated), one must conclude that during

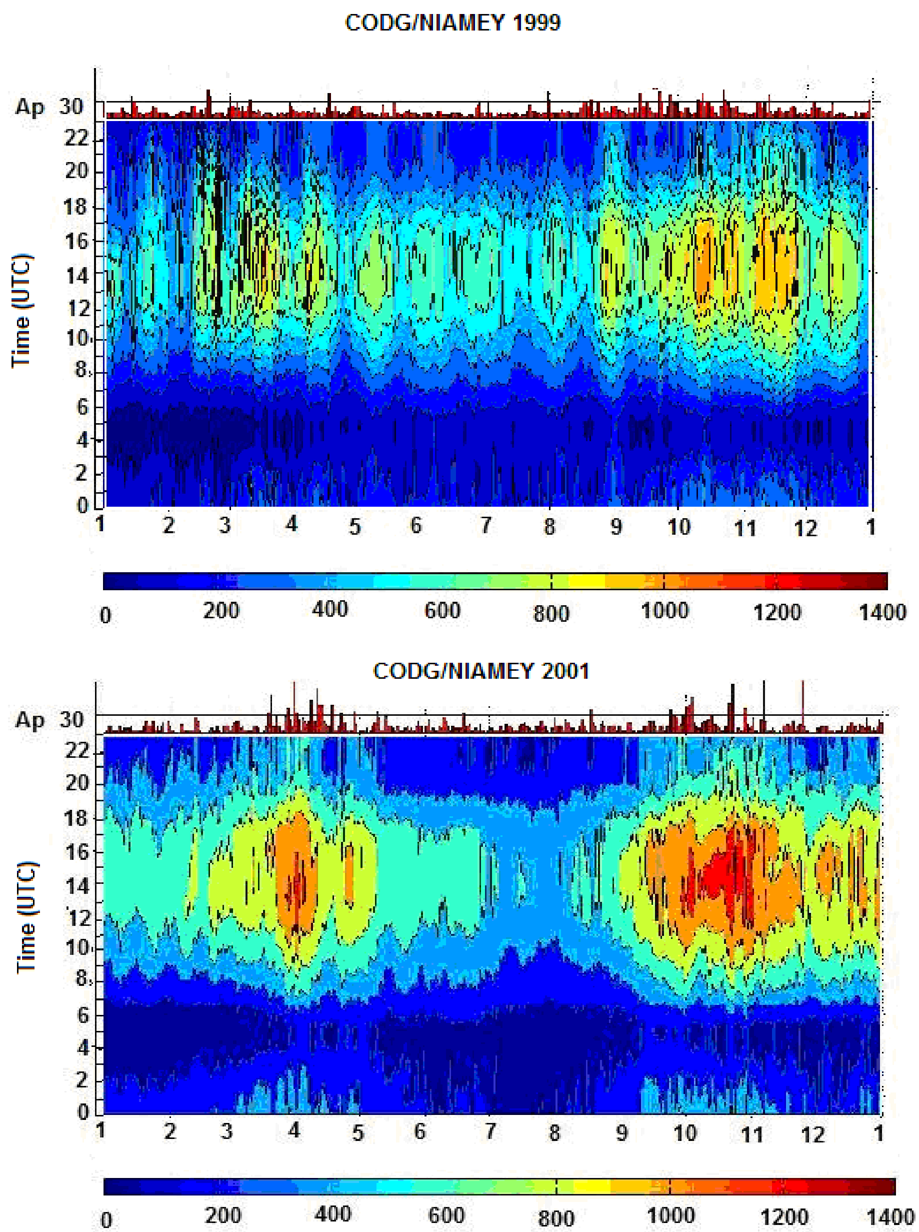

Figure 7. Monthly CODG TEC evolution for year a) 1999 b) 2001.

2001 the equinoctial asymmetry may be provoked by CMEs.

c) CODG TEC asymmetry source according to pixel diagrams

Figure 8 shows pixel diagrams for year 1999 (top panel) and year 2001 (bottom panel). Each line of the pixel shows a 27-day rotation, and successive lines solar rotations. Each number is the daily average of aa index. Shock activity started by non-recurrent sudden storm commencement (SSC) days (http://isgi.unistra.fr/data_download.php) (indicated by circle) with one, two or three days' duration and identified in pixel diagram by olive red and/or red colours. Recurrent activity is characterized by recurrent red or olive red colours without begging SSC days. Quiet days activity is given by white and blue colours with the other days contributing to fluctuating activity. Each class of activity can be shown in Figure 8.

It emerges from Figure 8 with respect to the work of Ouattara (2009) that asymmetries are more due to intense solar activity during October month than during March month. In pixel diagram of the year 1999 (Figure 8a), the asymmetry results from fluctuating activity due to

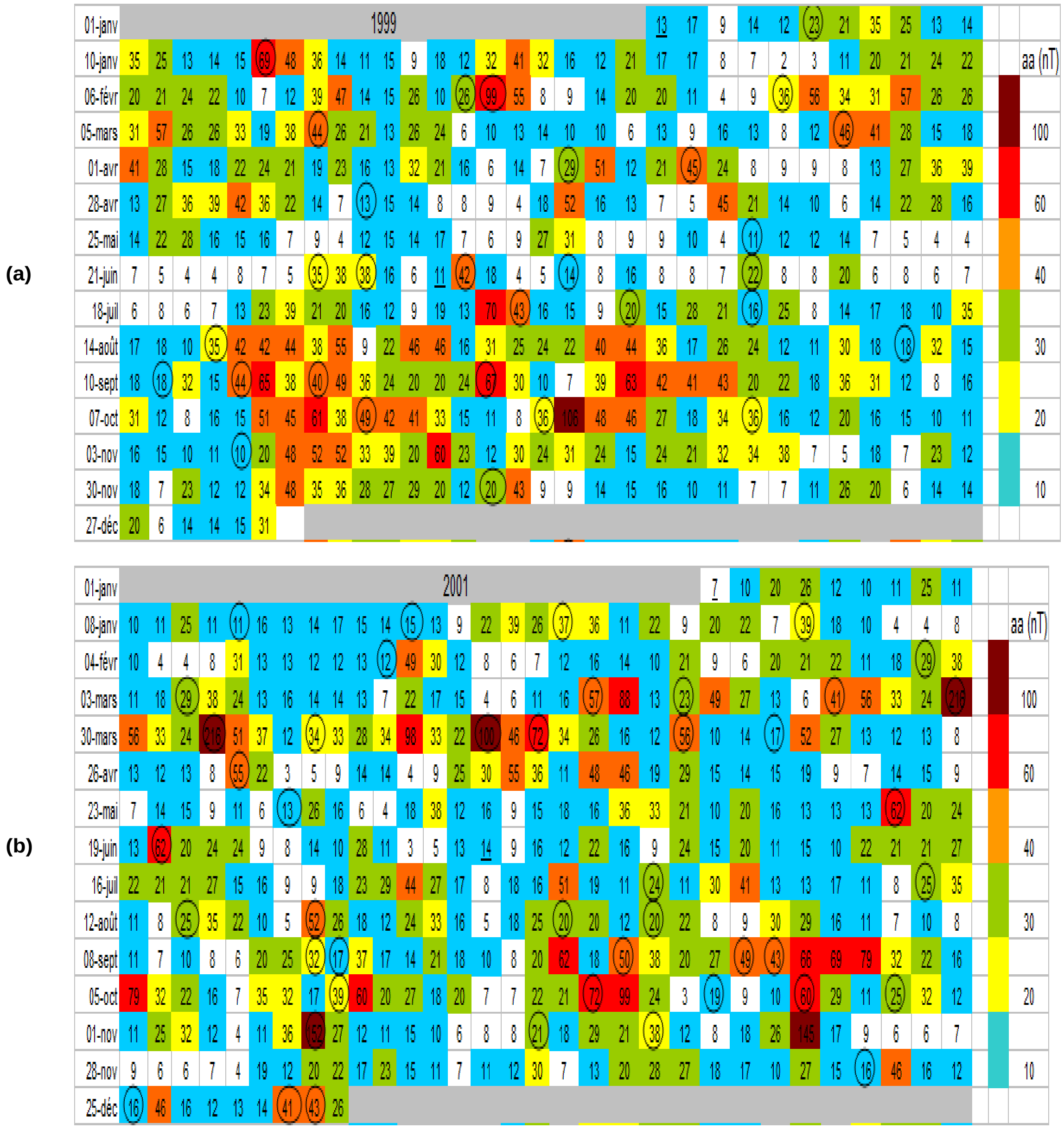

Figure 8. Pixel diagrams of years 1999 (panel a) and 2001 (panel b).

the fluctuating solar wind (Ouattara, 2009) provoked by the fluctuation of solar neutral sheet (Legrand and Simon, 1989). In pixel diagram of the year 2001 (Figure 8b), the asymmetry is due to CMEs (Ouattara, 2009). Thus, the results obtained from the analysis of pixel diagrams and from the use of Ap index are the same.

d) CODG TEC asymmetry source according to the results of Cliver et al. (2002)

Cliver et al. (2002) gives the dates of peaks of semi-annual variation of geomagnetic index aa during quiet time and disturbed period and the mechanism that likely explained such variation. The periods of the peak occurrence obtained from their work is given in the top of Tables 1 (disturbed period) and 2 (quiet period). For analysing the results of this research, the gap (shown by Δ in the table) between their peak date with respect to the mechanism and the observed peak date was determined. Observed dates are indicated in red and the possible mechanism is given by minimum value of Δ. This minimum value is highlighted in green.

Tables 1 and 2 show that the semi-annual variation of CODG TEC at Niamey during the years 1999 and 2001 is managed by Russell McPherron mechanism.

Table 1. Disturbed period (aa >20 nT).

Parameter		Spring maximum	Fall Maximum	Summer minimum	Winter minimum
Axial		7 March	9 September	7 June	8 December
Russell McPherron		7 April	11 October	7 July	6 January
Equinoctial		21.1 March	23.4 September	21.8 June	22.3 December
1999	Observed date	14.6 March	16.6 November	2.6 July	23.5 January
	Δ Axial (days)	+7.6	+68.6	+25.6	+46.5
	Δ Russell McPherron (days)	-23.4	**+36.6**	**-4.4**	**+17.5**
	Δ Equinox (days)	**- 6.5**	+ 54.2	+ 11.8	+ 33.2
2000	Observed date	06.6 April	27.5 October	12.6 June	20.5 January
	Δ Axial (days)	+30.6	+48.5	+5.6	+43.5
	Δ Russell McPherron (days)	**-0.4**	**+16.5**	-24.4	**+14.5**
	Δ Equinox (days)	+ 16.5	+ 34.1	**- 9.2**	+ 32.2
2001	Observed date	14.7 April	10.5 November	15.5 July	26.5 January
	Δ Axial (days)	+38.7	+62.5	+38.5	+49.5
	Δ Russell McPherron (days)	**+7.7**	**+30.5**	**+8.5**	**+20.5**
	Δ Equinox (days)	+ 24.6	+ 48.1	+ 23.7	+ 35.2
2002	Observed date	03.6 March	28.5 October	29.6 July	24.6 December
	Δ Axial (days)	**-3.4**	+49.5	+52.6	+16.6
	Δ Russell McPherron (days)	-34.7	**+17.5**	**+22.6**	-12.4
	Δ Equinox (days)	- 14.5	35.1	+ 37.8	**+ 02.3**
2003	Observed date	10.6 March	28.5 October	20.5 July	05.6 December
	Δ Axial (days)	**+3.6**	+49.5	+43.5	**-2.4**
	Δ Russell McPherron (days)	-27.4	**+17.5**	**+13.5**	-31.4
	Δ Equinox (days)	- 10.5	35.1	+ 28.7	- 16.7
2004	Observed date	03.6 April	23.6 October	17.6 July	06.5 December
	Δ Axial (days)	+27.6	+44.6	+40.6	**-1.5**
	Δ Russell McPherron (days)	**-3.4**	**+12.6**	**+10.6**	-30.5
	Δ Equinox (days)	+ 13.5	+ 30.2	+ 25.8	- 15.8
2005	Observed date	14.6 March	17.6 September	02.6 July	02.6 December
	Δ Axial (days)	+7.6	+8.6	+25.6	**-5.4**
	Δ Russell McPherron (days)	-23.4	-23.4	**-4.4**	-34.4
	Δ Equinox (days)	**- 6.5**	**- 5.8**	+ 10.8	- 19.7
2006	Observed date	14.7 April	10.5 November	05.5 July	23.7 January
	Δ Axial (days)	+38.7	+62.5	+28.5	+46.7
	Δ Russell McPherron (days)	**+7.7**	**+30.5**	**-1.5**	**+17.7**
	Δ Equinox (days)	+ 24.6	+ 48.1	+ 13.7	+ 32.4
2007	Observed date	25.6 March	03.6 October	14.6 June	17.6 December
	Δ Axial (days)	+18.7	+24.6	+7.6	+9.6
	Δ Russell McPherron (days)	-12.4	**-7.4**	-22.4	-19.4
	Δ Equinox (days)	**+ 4.5**	+ 10.2	**- 7.2**	**- 4.7**
2008	Observed date	23.6 April	12.6 October	12.6 July	23.6 December
	Δ Axial (days)	+47.6	+33.6	+35.6	+15.6
	Δ Russell McPherron (days)	**+16.6**	**+1.6**	**+5.6**	-13.4
	Δ Equinox (days)	+ 33.5	+ 19.2	+ 20.8	**+ 1.3**

Table 2. Quiet period (aa≤ 20 nT).

Parameter		**Spring maximum**	**Fall maximum**	**Summer minimum**	**Winter minimum**
Axial		7 March	9 September	7 June	8 December
Russell McPherron		7 April	11 October	7 July	6 January
Equinoctial		21.1 March	23.4 September	21.8 June	22.3 December
1999	Observed date	18.6 March	26.6 November	4.6 July	04.5 January
	Δ Axial (days)	+9.6	+78.6	+27.6	+27.5
	Δ Russell McPherron (days)	-19.4	**+43.4**	**-2.4**	**-1.5**
	Δ Equinox (days)	**- 2.5**	+ 64.2	+ 12.6	+ 13.2
2000	Observed date	13.5 April	29.6 October	01.5 June	13.5 January
	Δ Axial (days)	+37.5	+50.6	-5.5	+36.5
	Δ Russell McPherron (days)	**+6.5**	**+18.6**	-35.5	**+7.5**
	Δ Equinox (days)	+ 24.4	+ 36.2	**- 20.6**	+ 22.2
2001	Observed date	29.6 April	03.5 October	12.6 July	11.5 January
	Δ Axial (days)	+53.6	+24.5	+35.6	+34.5
	Δ Russell McPherron (days)	**+22.6**	**-7.5**	**+5.6**	**+5.5**
	Δ Equinox (days)	+ 39.5	+ 43.1	+ 20.8	+ 20.2
2002	Observed date	13.5 March	13.5 October	28.5 July	10.6 December
	Δ Axial (days)	**+6.5**	+34.5	+51.5	**+2.6**
	Δ Russell McPherron (days)	-24.5	**+2.5**	**+21.5**	-26.4
	Δ Equinox (days)	- 7.6	+ 20.1	+ 36.7	- 11.7
2003	Observed date	12.7 March	27.6 October	22.6 July	01.6 December
	Δ Axial (days)	+5.7	+48.6	+45.6	**-6.4**
	Δ Russell McPherron (days)	-25.3	**+16.6**	**+15.6**	-35.4
	Δ Equinox (days)	**- 8.9**	+ 34.2	+ 30.8	- 20.6
2004	Observed date	01.6 April	27.6 October	01.4 July	03.5 December
	Δ Axial (days)	+25.6	+48.6	+24.4	**-4.5**
	Δ Russell McPherron (days)	**-5.4**	**+16.6**	**-5.6**	-31.5
	Δ Equinox (days)	+ 22.7	+ 34.2	+ 09.6	- 18.8
2005	Observed date	24.7 March	23.6 September	04.6 August	04.5 December
	Δ Axial (days)	+17.7	+14.6	+58.6	-3.5
	Δ Russell McPherron (days)	-13.3	-17.4	**+28.6**	-32.5
	Δ Equinox (days)	**+ 3.6**	**+ 00.2**	+ 43.8	**- 17.8**
2006	Observed date	29.6 April	08.5 November	23.6 August	02.5 January
	Δ Axial (days)	+53.6	+65	+77.5	+25.5
	Δ Russell McPherron (days)	**+22.6**	**28.5**	**+47.6**	**-3.5**
	Δ Equinox (days)	+39.5	+ 46.1	+ 62.8	+ 11.2
2007	Observed date	01.5 April	15.6 October	08.6 August	04.5 December
	Δ Axial (days)	+25.5	+36.6	+62.6	**-3.5**
	Δ Russell McPherron (days)	**-5.5**	**+4.6**	**+32.6**	-32.5
	Δ Equinox (days)	+ 11.4	+ 22.2	+ 47.8	-17.8

Table 2. Contd.

2008	Observed date	26.6 March	28.6 October	15.6 July	12.5 December
	∆ Axial (days)	+19.6	+49.6	+38.6	+4.5
	∆ Russell McPherron (days)	-11.4	**+17.6**	**+8.6**	-24.5
	∆ Equinox (days)	**+ 5.5**	+ 35.2	+ 23.8	**- 9.8**
2009	Observed date	25.7 March	22.6 October	20.5 August	14.5 January
	∆ Axial (days)	+18.7	+43.6	+74.5	+37.5
	∆ Russell McPherron (days)	-12.3	**+11.6**	**+44.5**	**+8.5**
	∆ Equinox (days)	**+ 4.6**	+ 29.2	+ 59.7	+ 23.2

Table 3. Synthesis of mechanism occurrence.

Season	Asymmetry mechanism	Mechanism occurrence
Quiet period		
Spring	Axial	2/11
	McPherron	4/11
	Equinoctial	5/11
Fall	Axial	
	McPherron	10/11
	Equinoctial	1/11
Summer	Axial	
	McPherron	10/11
	Equinoctial	1/11
Winter	Axial	4/11
	McPherron	6/11
	Equinoctial	1/11
Disturbed period		
Spring	Axial	2/10
	McPherron	5/10
	Equinoctial	3/10
Fall	Axial	
	McPherron	9/10
	Equinoctial	1/10
Summer	Axial	
	McPherron	8/10
	Equinoctial	2/10
Winter	Axial	3/10
	McPherron	4/10
	Equinoctial	3/10

The presence of equinoctial peak asymmetry for the year 2001 cannot be explained by the change mechanism for it is the same mechanism for March/April and for September/October.

During year 1999, the asymmetry may be explained by the change of mechanism. During March/April, the mechanism is equinoctial and during September/October it is Russell McPherron.

Only the year 2006 semi-annual variation is completely explained by Russell McPherron mechanism and that during both quiet and disturbed periods.

The synthesis (Table 3) of the mechanism that occurs during the 11 years involved (quiet time) and 10 years involved (disturbed period) shows that Russell McPherron mechanism can be used to explain the CODG TEC semi-annual variation at Niamey Station.

Conclusion

Seasonal CODG TEC presents semi-annual variation with maximum TEC observed between 1000 - 1500 UTC. The peak is seen at 1400 UTC. The seasonal CODG TEC shows equinoctial peak asymmetry. March/April peak amplitude is higher than that of September/October except during 1999 and 2001. Ap values analysis and pixel diagrams investigation show that peak asymmetry is due to moderate solar wind during 1999 and similar to CMEs during 2001. This study argues that in 2001 the asymmetry cannot be explained by the change in solar activity while this situation seems to be the cause of the asymmetry observed during 1999. The overview of TEC behaviour shows that Russell McPherron mechanism manages the semi-annual variation of TEC at Niamey station.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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