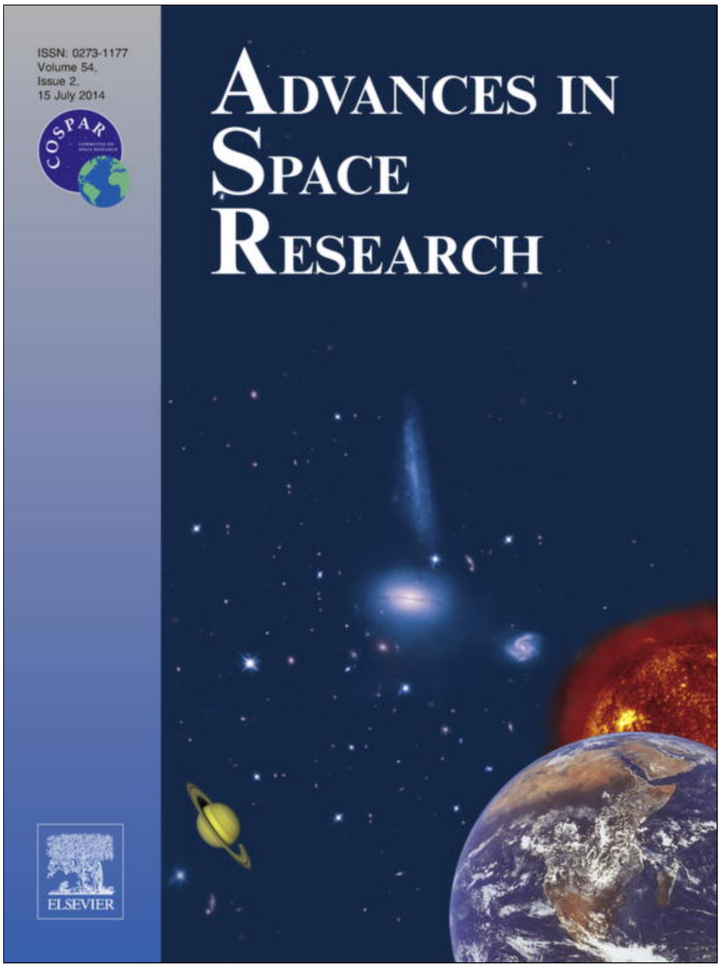
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Quasi-biennial oscillation in GPS VTEC measurements

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Abstract

The quasi-biennial oscillation, QBO, a well known periodicity in the equatorial stratospheric zonal winds, is also found in ionospheric parameters and in solar and geomagnetic activity indices. Many authors speculated about the link between the QBO in solar and geomagnetic activity and the QBO in atmospheric parameters. In this work we analyze the presence of the QBO in the ionosphere using the Vertical Total Electron Content (VTEC) values obtained from Global Navigation Satellite System (GNSS) measurements during the period 1999–2012. In particular, we used IONEX files, i.e. the International GNSS Service (IGS) ionospheric products. IONEX provide VTEC values around the world at 2-h intervals. From these data we compute global and zonal averages of VTEC at different local times at mid and equatorial geomagnetic latitudes. VTEC and Extreme Ultra Violet (EUV) solar flux time series are analyzed using a wavelet multi resolution analysis. In all cases the QBO is detected among other expected periodicities.

Since the main source of variation of free electrons in the ionospheric F2 region, where the maximum concentration occurs, is solar EUV radiation, we conclude that the most important cause attributable to QBO in the ionosphere is the quasi-biennial variability of EUV solar flux. Both QBOs are observed to vary in phase.

The percentage of the total signal of the ionospheric QBO at the local times of the maximum photoionization is around 15% independent of magnetic latitude while the respective percentage of the total energy for the EUV solar flux is about 18%.

Keywords: Quasi biennial oscillation; Wavelet; Global IGS VTEC maps

1. Introduction

The term Quasi-Biennial Oscillation (QBO) is commonly referred to the downward alternating easterly and westerly winds at equatorial stratosphere with a variable period of 26 to 28-months. The QBO is the main variation of the zonal wind in the equatorial stratosphere (Reed et al., 1961; Naujokat, 1986) and prevails over seasonal variations at heights of 15 to 30 km (200 to 10 mb).

Although it is well established that the QBO is driven primarily by internal wave dynamics from the entire tropical atmosphere (Baldwin et al., 2001), a possible modulation of the QBO via external forcing cannot be ruled out (Lu and Jarvis, 2011). There is evidence that some of the QBO stratospheric variability could be indirectly modulated by UV solar radiation (Salby and Callaghan, 2000; McCormack, 2003; McCormack et al., 2007; Lu and Jarvis, 2011).

It is also worth noting that periodic phenomena with quasi-biennial periods were frequently found in solar

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parameters related to the heliomagnetic field, although no clear physical mechanism has been suggested (Zaqarashvili et al., 2010).

Several authors (Obridko and Shelting, 2001; Badalyan et al., 2005, 2008; Zaqarashvili et al., 2010; Badalyan and Obridko, 2011; Vecchio et al., 2012; Simoniello et al., 2013) have pointed to a Quasi-Biennial periodicity in the North–South asymmetry of solar activity. This effect is demonstrated by analyzing three different indices: asymmetry of brightness of the coronal green line 530.3 nm, summarized sunspot areas and total sunspot group numbers.

Additionally, several authors have also identified a QBO in geomagnetic field perturbations during quiet days analyzing data from low and mid-latitude stations. Stacey and Westcott (1962), in Olsen (1994) attributed this oscillation to the extension of the equatorial stratospheric QBO to ionospheric heights. Yacob and Bhargava (1968), in Kane (1995) argued that its source was a biennial periodicity in solar UV radiation. Raja Rao and Joseph (1971) suggested an association between its mechanism and the equatorial electrojet; while Olsen (1994) and Olsen and Kiefer (1995) postulated that the observed QBO in geomagnetic variations could be caused by a dynamo action of a QBO in lower thermospheric winds. Jarvis (1996) arrived at conclusions similar to Olsen's when analyzing data of a high latitude station. Kane (1997) results indicate a strong geomagnetic QBO in the equatorial electrojet region only. He suggests that it may be related to the 50 hPa wind and rules out a solar origin. Sugiura and Poros (1977), in Kane (1997)) found a QBO in the Disturbance Storm Time index (Dst) highly correlated with a QBO in the sunspot numbers (Rz). According to them, the most likely cause for this oscillation is a solar modulation of the rate of plasma injection into the magnetosphere.

Zossi de Artigas and Elias (2005) analyzed the connection between the equatorial zonal wind and the Dst index. Although their study on the origin of the observed phenomena is inconclusive, the authors asseverated that the easterly phase of the stratospheric QBO happens during maximum solar activity and it is linked to higher solar irradiance as well as less ozone and lower temperatures in the Northern Polar Cap. This relationship is reversed during minimum solar activity.

Besides, other papers recognize a QBO in the Ionosphere. Based on data stations from near the northern equatorial anomaly crest Chen (1992) established that the yearly intensity change of the daily variation of the Equatorial Ionization Anomaly (EIA) is modulated by the QBO. He found that the zonal wind at 40 mb (20 km) is linearly correlated with f_0F_2. Moreover, in the east phase of the wind, f_0F_2 variance increases while in the west phase it decreases. The QBO signature appears to be stronger in the ionosphere in spring and autumn (Chen, 1992). Kane (1995) studied the critical frequency and the peak height of the F_2 layer (f_0F_2 and h_0F_2) at Juliusruh station (54.6 N, 13.4 E) for more than 30 years. These results were compared with solar indices (sunspots number -Rz- and 10.7 cm flux -F10.7-), geomagnetic index A_p and tropical stratospheric zonal winds. He found a QBO feature in both the ionospheric and geomagnetic parameters.

Kane (2005) performed an extensive statistical work looking for the QBO signal in different parameters: solar (Rz, sunspot areas F10.7, Lymann alpha, solar flare monthly group index SF, coronal green line intensity, X ray background, solar open magnetic flux); interplanetary (solar wind velocity, total magnetic field, solar magnetic open fluxes at different latitudes, solar proton fluxes), geomagnetic (Dst, A_p) and lower atmospheric (El Niño-Southern Oscillation indexes ENSO, winds, temperatures, O_3 and CO concentrations). He showed that even when the phenomena are named in the same way (QBO), they are qualitative different. Moreover, he distinguished between four different regimes: in solar indexes at solar latitudes lower than 45°; in the interplanetary and geomagnetic parameters; in the tropical stratospheric zonal winds and the ENSO phenomena.

Mansilla et al. (2009) reported a QBO signal in the f_0F_2 time series measured in Tucuman (26.9°S, 65.4°W) near the southern crest of the equatorial anomaly for the period 1958–1987. They found out the quasi biennial period at different local times with the greater amplitudes at noon and midnight.

Echer (2007) highlights that there are at least three regimens that could be responsible for the ionospheric variation. In the first scenario, the QBO in solar activity indices could force the variability of the ionospheric parameters. The second scenario is the QBO in the stratosphere influencing the propagation of atmosphere waves, which propagate upwards into the ionosphere F region modulating the ionization and neutral wind circulation. In the last scenario, the QBO in the IMF (Interplanetary Magnetic Field) influences both the particle precipitation and current system in the ionosphere.

In this work we focus on just one of his proposed scenarios: the importance of the QBO detected in solar activity that directly influences the ionospheric behavior. Thus, we concentrate on a partial explanation for the observed QBO effect in the ionospheric behavior which is detected through the analysis of the variability of the vertical Total Electron Content (VTEC) obtained from GPS (Global Positioning System). To this aim, we studied the QBO present in Extreme Ultra Violet (EUV) solar radiation responsible, not only for the heating in the thermosphere, but also for the ionization of neutral species, forming thus the ionosphere (Dwivedi and Mahajan, 2005).

2. Data and methods

The global ionospheric maps computed using GPS observations are available for the users as a file in the IONosphere map EXchange (IONEX) format (Schaer et al., 1998). The file contains all the information relative to the computation process and the VTEC information are presented in the form of a grid of 2.5 degrees in latitude and 5 degrees in longitude (Meza et al., 2012).

The IONEX format allows the storage of snapshots of the electron density (including associated root mean square information) referring to particular epochs and to a 2 or even 3 dimensional, Earth-fixed grid. IONEX data supply a good estimation of the worldwide VTEC. These data provide VTEC values around the world at intervals of 2.5 degrees in latitude and 5 degrees in longitude. Global IGS VTEC maps during almost a solar cycle (from January 1999 to December 2012) are used in this work. These VTEC maps show a global portrait of the ionosphere every two hours. Therefore, the main geographical VTEC variation is due to the ionization produced by solar radiation. Since we are not interested in analyzing that effect but the ionospheric response to similar conditions on different locations, we organized the VTEC data as follows.

(A) Three ionospheric regions were considered: two mid-latitude zonal bands between 30° and 45° geomagnetic latitude for both hemispheres, and the equatorial belt between +/− 20° geomagnetic latitude.
(B) From each daily global data set, composed by twelve VTEC maps, two maps were constructed, which corresponds to 1 pm and 4 pm local time in the selected ionospheric regions.

The time series were constructed in the following way: given the IONEX file at 0 hs UTC for a selected day, we first pick out the ionospheric mean-latitude and equatorial bands; then by using the longitude information we select all the grid points at 1 pm and 4 pm local time. Afterward, the representative average VTEC value for each ionospheric region is computed among the selected grid points. This process was repeated for the 12 maps of each day. Finally, a daily VTEC average value was computed for each mid-latitudes and equatorial regions at 1 pm and 4 pm, respectively. The complete data set consists of 6 series of daily VTEC, one series for each latitude band and one for each local time, during the period 1999–2012. It is important to stress that there are no further processes applied to the data besides this sorting.

The data of the solar EUV flux, in units of 10^{10} photons $cm^2\ s^{-1}$, is obtained from The Solar EUV Monitor (SEM) on-board the Solar and Heliospheric Observatory (SOHO) satellite. The daily average full solar disk EUV flux was recorded in the 0.1–50 nm spectral band and measured at 1 A.U. (astronomical unit).

From the 6 different VTEC series and the solar EUV flux time series, all of them at daily basis, 10-day averages were calculated.

In this work we focus on the importance of the QBO in solar activity that directly influences VTEC variability. VTEC is the integral of the electron density respect to the height and the maximum contribution comes from the F_2 region (300–450 km), where the photoionization is mainly produced by the ultraviolet solar radiation.

3. Multiresolution analysis

The Multiresolution Analysis (MRA) of a given signal $x(t)$ decomposes it in a low-frequency approximation at scale J, $A_J(t)$, and a set of details, $D_j(t)$, for each scale $j = 1, 2, 3 \ldots, J$. The $A_J(t)$ represents the average of the signal $x(t)$ at the time scale 2^J and the jth detail $D_j(t)$ represents the change of $x(t)$ on a time scale 2^{j-1}.i.e., the information removed when going from an approximation level to another, i.e., $D_j(t) = A_{j-1}(t) - A_j(t)$ (Kumar and Foufoula-Georgiou, 1997; Rincón Rivera, 2007).

In brief, the original time series is decomposed into series of approximations and details following the successive filtering scheme proposed by Mallat (1989). In the first step, the signal is separated into one approximation and its respective detail. The approximation is decomposed in turn and after successive iterations, a lower resolution detail of the original signal is obtained.

The formulas of the discrete wavelet transform are used to compute the coefficients and approximate signals at different scales. Thus, when expressed in terms of wavelets coefficients, the jth approximation of $x(t)$ is

$$A_j(t) = \sum_k a_{j,k}\phi_{j,k}(t) \tag{1}$$

where the coefficients $a_{j,k}$ give the discrete sampled values of $x(t)$ at resolution j and location index k (Kumar and Foufoula-Georgiou, 1997) and $\phi_{j,k}(t)$ is a function of the scaling function ϕ_0 (Mallat, 1989), acting as a low pass filter. They can be written as

$$a_{j,k} = \int x(t)\ \phi_{j,k}(t)\ dt \quad \phi_{j,k}(t) = 2^{-j/2}\,\phi_0(2^{-j}t - k) \tag{2}$$

Also the details $D_j(t)$ can be written as a weighted summation of dilated-and-translated wavelet mother $\psi_{j,k}(t)$ (Kumar and Foufoula-Georgiou, 1997; Rincón Rivera, 2007)

$$D_j(t) = \sum_{k=-\infty}^{\infty} D_{j,k}\,\psi_{j,k}(t) \tag{3}$$

where the $D_{j,k}$ coefficients are the reconstruction of the wavelet analysis, and they results measure the contribution of the scale 2^j at location $k2^j$. Thus,

$$D_{j,k} = \int x(t)\psi_{j,k}(t)dt \tag{4}$$

Knowing that,

$$A_{j-1}(t) = A_j(t) + D_j(t); \quad j = 1, 2, \ldots, J \tag{5}$$

By using MRA in the time domain the original signal $x(t)$ can be written as

$$x(t) = A_J(t) + \sum_{j=1}^{J} D_j(t); \quad j = 1, 2 \ldots, J \tag{6}$$

In this application $J = 6$ and $x(t)$ represents the *EUV* signal and each *VTEC* time series. Thus, considering one VTEC series for each ionospheric latitude band (mid-latitude North, mid-latitude South and Equatorial) and one for each local time (1 pm and 4 pm), we have a total of 6 VTEC data series.

After applying a one-dimensional wavelet decomposition using a Mayer mother wavelet to each data series, we calculate the percentage of total signal amplitude corresponding to detail j as

$$Amp_j = 100.\sqrt{\frac{E_j}{E_T}}; \quad j = 1, 2 \ldots, J \tag{7}$$

where E_j is the wavelet energy in the j scale: $E_j = \sum_{k=1}^{q_j} D_{j,k}^2$, j stands for the scale and q_j is the longitude of the wavelet coefficients vector corresponding to the scale j; and $E_T = \sum_{j=1}^{J}\sum_{k=1}^{q_j} D_{j,k}^2$ represents the total wavelet energy.Consequently, in this analysis the percentage of QBO amplitude ($j = 6$) with respect to the total amplitude is

$$Amp_{QBO} = 100 \,.\sqrt{\frac{E_6}{E_T}} \tag{8}$$

4. Results

The wavelet MRA was applied to the solar EUV flux data series as well as the six VTEC time series (the north mid-latitude, the equatorial and the south mid-latitude zonal belts, each computed at 1 pm and 4 pm). Because the IONEX data files are available every 2-h, the selected local times represent the maximum photoionization conditions in the ionosphere at the selected magnetic latitude regions. Therefore taking into account that, according to the Chapman theory, there is a strong relation between the electrons production and the intensity of the radiation (Chapman, 1931), we can express the following relationship:

$$\frac{\Delta\,\mathrm{TEC}}{\mathrm{TEC}} \propto \frac{\Delta\,\mathrm{EUV}}{\mathrm{EUV}} \tag{9}$$

where Δ represents the variation.

Fig. 1 shows the 6-level decomposition for the 10-day average EUV data series from 1999 till the end of 2012. The main periodic characteristics are the QBO signal at level 6 (D6, 841 days), the annual and semi-annual variations at D5 (360 days) and D4 (180 days) levels, followed by seasonal variations (D3, 120 days) and low periods (D2, 72 days and D1, 26 days). Clearly seen are the amplitude differences between maximum and minimum periods of solar activity. The same analysis is shown in Fig. 2 for one VTEC series. The 10-day average equatorial VTEC data series at 1 pm local time was chosen as an example; although the behavior of the remaining 5 VTEC time series is quite similar in spite of the obvious differences in

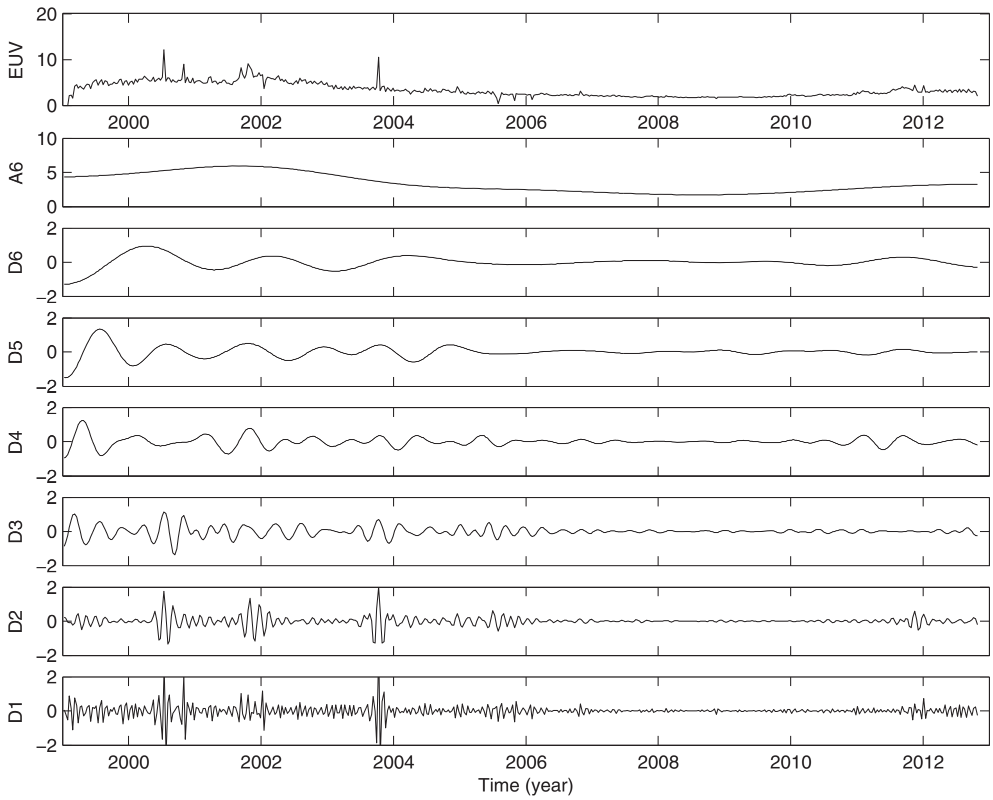

Fig. 1. Levels of the wavelets multi-resolution analysis for EUV data series. From top to bottom: 10-day average of EUV flux from SOHO in units of 10^{10} photons cm^2 s^{-1}, A_6 scaling level and the respective details, D_6 (QBO, 16–32 months), D_5 (12 months), D_4 (6 months), D_3 (4–5 months), D_2 (~2 months) and D_1 (~1 month).

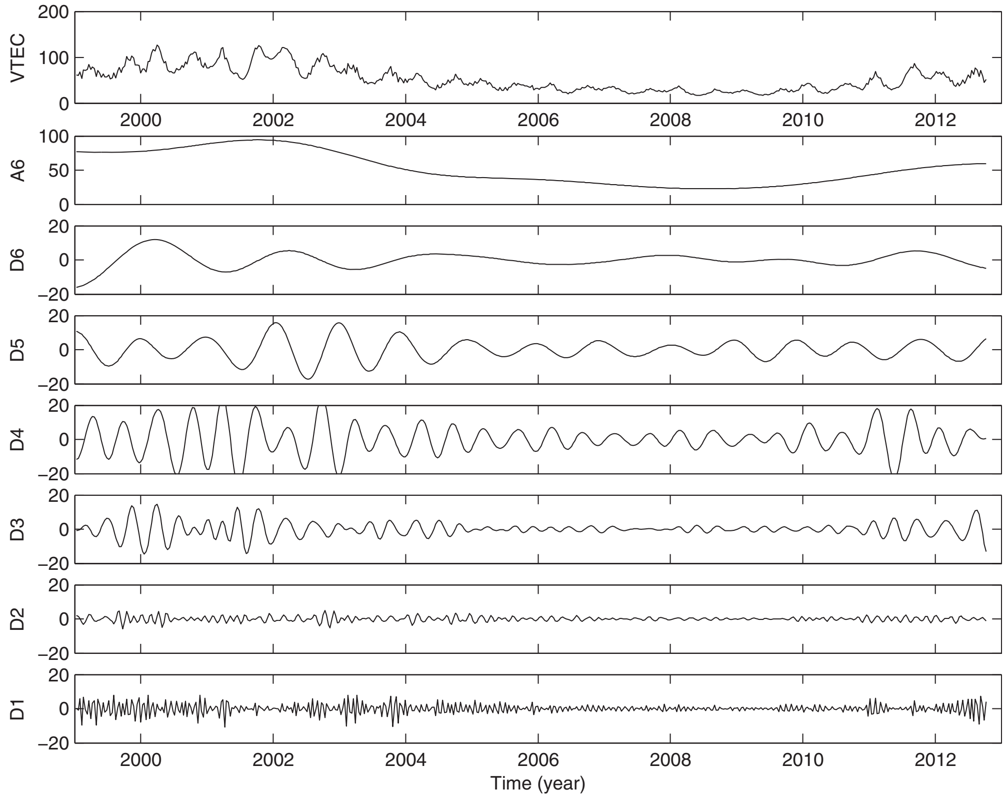

Fig. 2. Levels of the wavelets multi-resolution analysis for VTEC data series at equatorial magnetic latitudes and at 1 pm local time. From top to bottom: 10-day average of VTEC from GPS (IONEX files) in TECU, A_6 scaling level and the respective details, D_6 (QBO, 16–32 months), D_5 (12 months), D_4 (6 months), D_3 (4–5 months), D_2 (~2 months) and D_1 (~1 month).

amplitudes. This figure shows similar periodic features: a QBO in D6, annual and semi-annual periods in D5 and D4, periods of about 4 month in D3 and lower periods in D2 and D1.

The statistical meaning of the periodicities was computed following a time series iterative regression analysis (Rigozo et al., 2005). Following this iterative least square fit method, the periodicities were considered significant if their amplitudes are larger than 3 times their respective standard deviation. This criterion is more conservative than Echer (2007), who considered that the periodic terms are significant if the respective amplitudes exceed 2 times their standard deviation.

Thus, for all the time series analyzed the significant periods are: the QBO, annual, semi-annual and seasonal (D1 to D3). Fig. 3 shows the QBO signal for the three magnetic latitude belts at 1 pm along with EUV, where is also evident the amplitude modulation due to the Schwabe cycle (11-year), which cannot be represented due to data length.

In order to statistically test the hypothesis of direct influence of solar EUV radiation leading the QBO in ionospheric density, we computed the energy and the amplitude for the solar EUV time series together with all VTEC series. Table 1 shows the percentage of the QBO (D6) signal amplitude with respect to the total amplitude for all the data time series. From Table 1, the QBO in VTEC values represents about 15% of its total amplitude while the QBO detected in solar EUV radiation has about 18% of the total amplitude. Because the similarity of these figures, considering the role of the EUV radiation in the existence of the ionosphere itself and the simplicity of the Chapman model to explain the main features of the ionospheric variability; we would say that quasi-biennial variations of EUV flux produced major QBO variations detected in the ionosphere.

In order to distinguish between high and low solar activity periods during the interval 1999–2013; the wavelet MRA was also applied to the solar EUV flux data series and the three VTEC time series (the north mid-latitude, the equatorial and the south mid-latitude zonal belts computed at 1 pm) from 1999 till the end of 2005 (high solar activity) and from 2006 till the end of 2012 (low solar activity). Table 2 shows the percentages of amplitude with respect to the total signal amplitude for each level 6 obtained during high and low solar activity.

Also, as expected, VTEC and EUV QBOs vary in phase presenting a high degree of correlation (~0.9). Anyway, we cannot rule out the existence of some other ionosphere-thermosphere coupling mechanism contributing to the observed ionosphere density variability.

5. Discussion

There is not yet a convincing explanation for the QBO observed in the solar EUV radiation. A possible explanation is given by Kononovich (2002) who argues that the

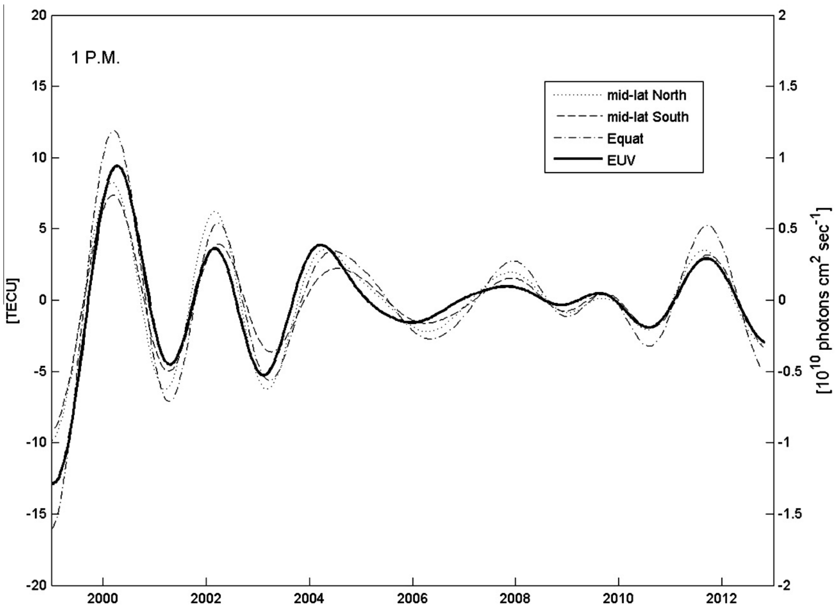

Fig. 3. QBO (D6 levels from wavelets MRA) time series for the Equatorial region, North and South mid-latitudes band at 1 pm local time. The thick line is QBO in EUV data.

Table 1
Percentage of the QBO (D6) signal amplitude with respect to the total amplitude for the range 1999 to 2012.

		1 pm.	4 pm.
VTEC	Mean latitudes North	13.39	13.6
IONEX	Equatorial	14.74	13.95
	Mean latitudes South	14.42	14.95
EUV (SOHO)		17.92	

Table 2
Percentage of the QBO (D6) amplitude with respect to the total amplitude discriminating high and low solar activity periods for the interval 1999–2012.

	High Solar Activity 1999–2005	Low Solar Activity 2006–2012
Mid-latitude Northern Hemisphere (VTEC)	16.60	4.93
Equatorial belt (VTEC)	15.37	3.97
Mid-latitude Southern Hemisphere (VTEC)	16.34	5.22
EUV (SOHO)	19.38	5.16

origin of the QBO in the Sun suggests a connection with the dynamical processes in the deeper layers of the star. Furthermore, Vecchio et al. (2010) observed that “quasi-biennial periodicity is a fundamental mode of solar variability” that affects the fluxes of solar and galactic cosmic rays and neutrinos. However QBO has been observed not only in solar activity parameters but also in geomagnetic ones by many authors.

By using 10-days VTEC average data extending from 1999 to 2012, we have analyzed the relationship between the quasi-biennial behavior of the net concentration of free electron in the F layer and the EUV solar flux. We assume that the form of the F_2 ionospheric layer and the way it varies during the day, obeys to a Chapman production function. Besides, considering that the solar EUV leads the production of plasma by photoionization around 300 km in the equatorial and mid-latitudes ionospheric regions, we can analyze the importance of the QBO of the solar flux in the observed ionospheric QBO behavior.

The percentage of the total energy of the QBO for VTEC in local times corresponding to the maximum of photoionization is around 14–15% at low and mid geomagnetic latitudes when we analyzed the whole time series (1999–2013), and this value descends from 16% to 5% when considering high and low solar activity respectively. Furthermore, the percentage of the total energy of EUV flux of the QBO signal detected is 18% and it varies in phase with VTEC QBO (Fig. 3) when we analyzed the complete 14-year period. Again the value changes from 19% to 5% if discriminating between high and low solar activity respectively. One might conclude that quasi-biennial variations of EUV flux produced major QBO variations detected in the ionosphere.

A weakening of the QBO amplitude during the descendent phase of the solar cycle is also noticeable from Fig. 3: greater amplitude at the beginning (coincident with maximum of solar cycle 23) than at the end of the period analyzed (coincident with minimum of solar cycle 23).

We found out an explanation for the observed QBO ionospheric effect, although the influence from another coupling mechanism from the geomagnetic field-ionosphere-middle atmosphere should not be ruled out.

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