Chapter 14

Comparison between the NeQuick Model and VTEC Estimation by GPS Measurements over Egypt

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1. Introduction

The most important measured feature in the ionosphere is the Total Electron Content (TEC) which is significant for the operation of the ground and space-based systems involving radio wave signal propagation. At the middle and lower ionosphere, the electron density exhibits a strong seasonal variation due to the change in the solar zenith angle and the solar radiation flux through the whole year. At the upper ionosphere and the F2 layer, the electron density is mostly affected by the plasma transport process, diffusion, electric fields and neutral wind motions. The most important seasonal feature is that NmF2 in winter is greater than NmF2 in summer. This phenomenon is called the seasonal anomaly.

This study uses the TEC-data obtained from two dual-frequency GPS receivers at Helwan and Alexandria, in Egypt. The receiver type, geographic and magnetic coordinates of these stations are shown in Table 1. Helwan station belongs to the Scintillation Network and Decision Aid (SCINDA) system which is a network of ground-based receivers that monitor the ionosphere at UHF and L-band [1]. The receiver tracks the constellation of visible GPS satellites but with a minimum 20° elevation cut off angle in order to minimize the multipath effect. For ALEX2 station, it is located at Centre d'Etudes Alexandrines and provides GPS observations with 30 seconds.

The NeQuick [2] is an ionospheric electron density model developed at the Aeronomy and Radio propagation Laboratory of The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, and at the Institute for Geophysics, Astrophysics and Meteorology (IGAM) of the University of Graz, Austria. It is based on the original profiler proposed by

Di Giovanni and Radicella, 1990 [3]. It allows calculating the electron concentration at any given location in the ionosphere and thus the Total Electron Content (TEC) along any ground-to-satellite ray-path by means of numerical integration. The basic inputs are: position, time and solar flux (or sunspot number) and the output is the electron concentration at the given location in space and time.

The NeQuick model divides the ionosphere into two regions [4]: the bottomside, up to the F 2-layer peak, consists of a sum of five semi-Epstein layers [5] and the topside is described by means of an only sixth semi-Epstein layer with a height-dependent thickness parameter.

In this paper, we present a preliminary comparison between GPS-TEC measurements and the NeQuick modelling results over Egypt. Using a combination of the above datasets together with NeQuick calculations, we conduct a statistical annual analysis about the ionospheric behaviors during the enhancing phase of the current solar cycle 24, showing the average behavior and solar activity dependence of GPS and NeQuick-derived TEC.

Observatory station	**Symbol**	**Geographic coordinates**		**Geomagnetic coordinates**		**Receiver type**
Helwan	HELW	29.86 °N	31.32 °E	26.91 °N	108.72 °E	GSV 4004B
Alexandria	ALEX2	31.19 °N	29.91 °E	28.46 °N	107.75 °E	LEICA GRX1200GGPRO

Table 1. A list of the ground-based GPS sites used in this study.

2. Analytical Formulation

According to the theory of radio wave propagation in ionosphere, the ionospheric delay (Δtion) is proportional to the Total Electron Content (TEC) along the signal path and inversely to the squared frequency (*f*) used [6].

$$\Delta t_{ion} = \frac{40.3}{f^{2}} TEC \tag{1}$$

Each of the 31 operational GPS satellites is broadcasting information on two frequency carrier signals L1=1.57542 GHz and L2=1.2276 GHz. Due to the dispersive nature of the ionosphere, the two radio signals are delayed while their phases are advanced. The receivers provide two different range measurements (known as Pseudorange, P1, P2), and two different phase measurements (φ1, φ1) corresponding to the two signals. The Differential Pseudorange (DPR) and the Differential Carrier Phase (DCP) are given (in TECU) as follows;

$$\mathrm{DPR} = \mathrm{A}\ \left(\mathrm{P2\text{-}P1}\right) \tag{2}$$

$$\mathrm{DCP} = \mathrm{B}\left[\varphi 1 - \left(f1/f2\right)\varphi 1\right] \quad (3)$$

The constants A and B have been determined such that the computed TEC has units of TECU (1 TECU=1016 el/m2) and are given by:

$$\mathrm{A} = 2.854\ \mathrm{TECU}/\mathrm{ns} \quad (4)$$

$$\mathrm{B} = 1.812\ \mathrm{TECU}/\mathrm{L1\ cycle} \quad (5)$$

By combining use of pseudorange and carrier phase, a higher precision of TEC estimation can be implemented.

$$\mathrm{TEC_R} = \mathrm{DCP} + < \mathrm{DPR} - \mathrm{DCP} > \mathrm{ARC} \quad (6)$$

The notation < >ARC in eq. (6) indicates an average taken over a phase connected arc (between successive cycle slips). The relative total electron content (TEC_R) provides an absolute estimate of total electron content prior to "calibration" by subtraction of the receiver and satellite differential biases.

$$\mathrm{TEC} = \mathrm{TEC_R} - \mathrm{A}\left(\mathrm{BR} - \mathrm{BS}\right) \quad (7)$$

where BR is the receiver differential code bias and BS is the satellite differential code bias. We use estimating for the satellite biases provided by the Center for Orbit Determination in Europe (CODE). These biases are available by FTP download as 30 days average with the mean satellite differential biases removed [8]. For ALEX2 station, the receiver bias contains a contribution from the satellite biases, but this is of no consequence in the calibration since both contributions are removed in the end. Another method for estimating the receiver bias is used at HELW station. The inter-frequency bias associated with a particular receiver is estimated late at night (between 03:00 and 06:00 LT) when the ionosphere is minimally structured, using an iterative approach that minimizes the variance of verticalized TEC measured along the different satellite links. The nightly estimated receiver bias is shown to be insensitive to the assumed centroid height used in the single-layer approximation of the ionosphere. A 14 day running average of the bias is used to minimize the effect of this variability on the calibrated TEC [6].

The verticalized TEC is estimated as follows:

$$VTEC = [\mathrm{TECR} - \mathrm{A}\left(\mathrm{BR} - \mathrm{BS}\right)] / \mathrm{M}(h_{pp}, \varepsilon) \quad (8)$$

where $\mathrm{M}(h_{pp}, \varepsilon)$ is the single layer mapping function of the ionosphere, defined as

$$\mathrm{M}(h_{pp}, \varepsilon) = \sec\left\{\sin^{-1}\left[R_E \cos\varepsilon / (R_E + h_{pp})\right]\right\} \quad (9)$$

where R_E is the Earth radius, ε is the GPS satellite elevation angle and $h_{pp}$is the height of ionospheric piercing point. This height may be determined using an ionospheric model, or held fixed at a value representative of typical conditions. In this work 350 Km has been used.

NeQuick calculates the ionospheric electron density profile by relying on three anchor points: E, F1 and F2 which represents the peaks of the different layers of the ionosphere. The electron density at any location is computed based on the characteristic parameters (peak electron density, peak height) of these anchor points. To describe the electron density of the ionosphere above 90 km and up to the peak of the F2 layer, the NeQuick uses a modified DGR (Di Giovanni-Radicella) profile formulation which includes five semi-Epstein layers [5] with modelled thickness parameters (B) [4]. Three profile anchor points are used; namely the E layer peak, the F1 peak and the F2 peak that are modelled in terms of the ionosonde parameters foE, foF1, foF2 and M(3000)F2. The NeQuick model computes the electron density by one to three Epstein layers. The shape of an Epstein layer is given by the following function [7]:

$$N_{Epstein}(h,\ h_{max},\ N_{max},\ B) = \frac{4Nmax}{\left(1 + \exp\left(\frac{h\ -\ hmax}{B}\right)\right)^2} \exp\left(\frac{h\ -\ hmax}{B}\right) \tag{10}$$

where Nmax is the layer peak electron density, hmax is the layer peak height and B is the layer thickness parameter.

In the median GPS calculations, the geomagnetic Kp and Ap indices were used in-order to eliminate the geomagnetic active days plus one day after and before. In the present study we run the model using the monthly smoothed sunspot number R12 for each hour for the coordinates of HELW and ALX2 stations. We therefore obtain a simulated VTEC values which are compared to the corresponding derived median VTEC-GPS measurements.

3. Results and discussion

A monthly plots and annual maps for VTEC were created for both GPS-receiver stations. These measurements were compared with the simulated results from NeQuick model to test the validation through several seasons (table 2). The GPS-VTEC values are taken each hour and the median for each month was founded. All the measurements and calculations were taken during the enhancing phase of the current solar cycle along 201, 2011, 2013 and 2014 years.

Season	Months
Winter	Dec ,Jan, and Feb.
Vernal Equinox	March, April, and May.
Summer	June, Jul, and Aug.
Autumnal Equinox	Oct., Nov. and Dec

Table 2. Seasonal classifications

The following figures 1, 3, 5 and 7 displays the monthly variations of the measured VTEC (continuous red line) and simulated (dashed blue line) data for HELW and ALEX2 stations during the years 2010, 2011, 2012 and 2013, respectively. Figures 2, 4, 6 and 8 shows a contour maps for the VTEC derived from GPS-RINEX files and NeQuick modeling at HELW and ALEX2 stations during the years 2010, 2011, 2012 and 2013, respectively.

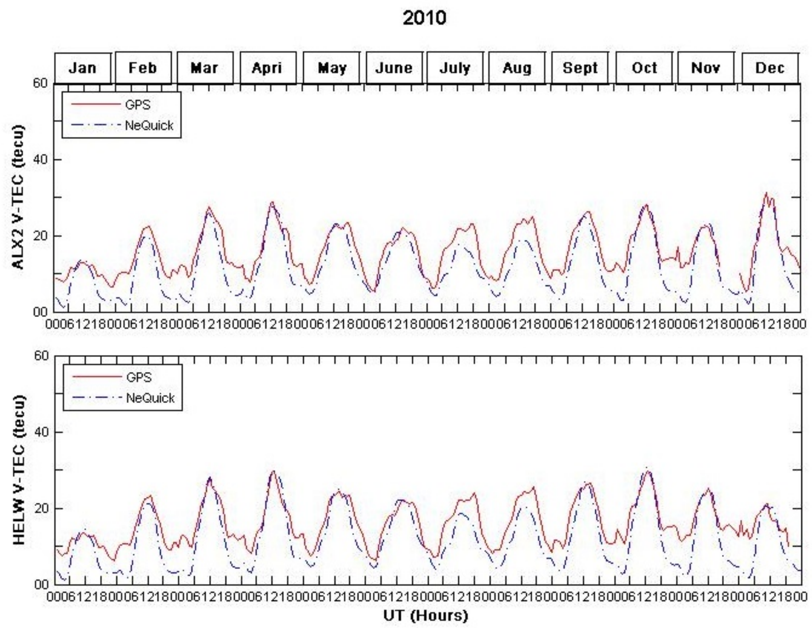

Figure 1. The monthly variations of the measured GPS-VTEC measured-(continuous red line) and the NeQuick simulated ones (dashed blue line) data taken from ALEX2 and HELW stations during the year 2010.

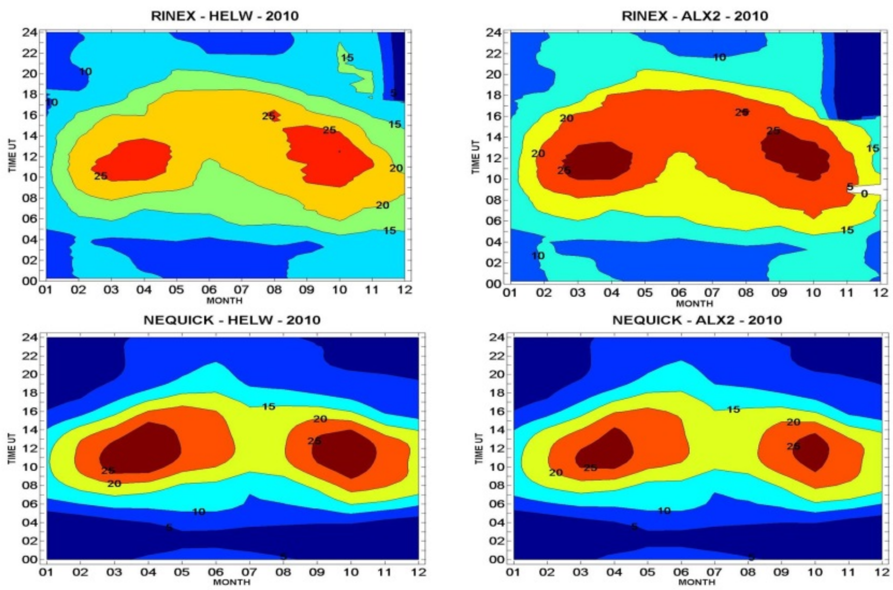

Figure 2. Contour map of VTEC measured and simulated data during the year 2010 at HELW and ALEX2 stations.

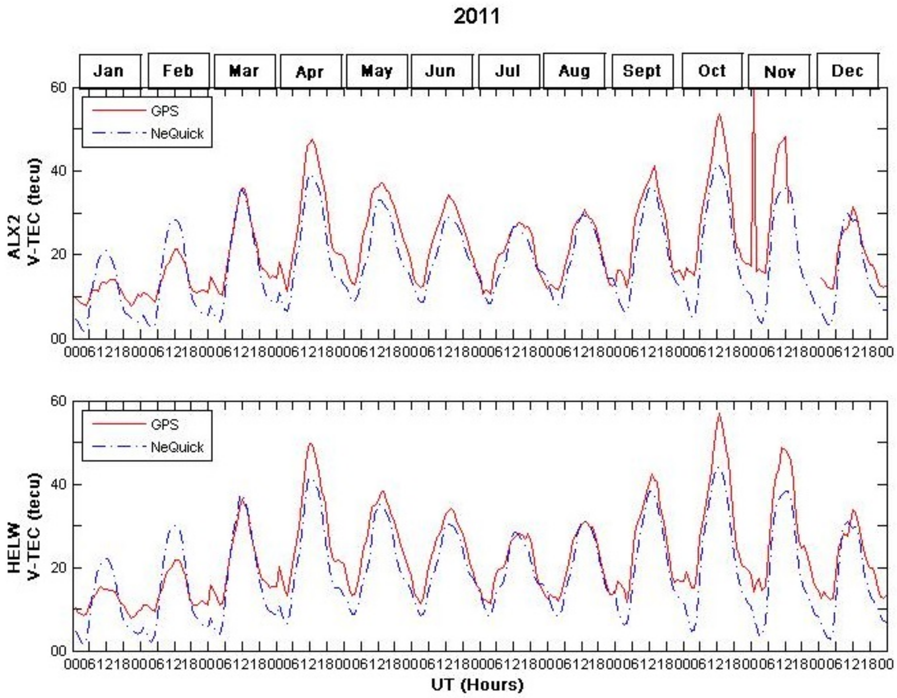

Figure 3. The monthly variations of the measured GPS-VTEC measured-(continuous red line) and the NeQuick simulated ones (dashed blue line) data taken from ALEX2 and HELW stations during the year 2011.

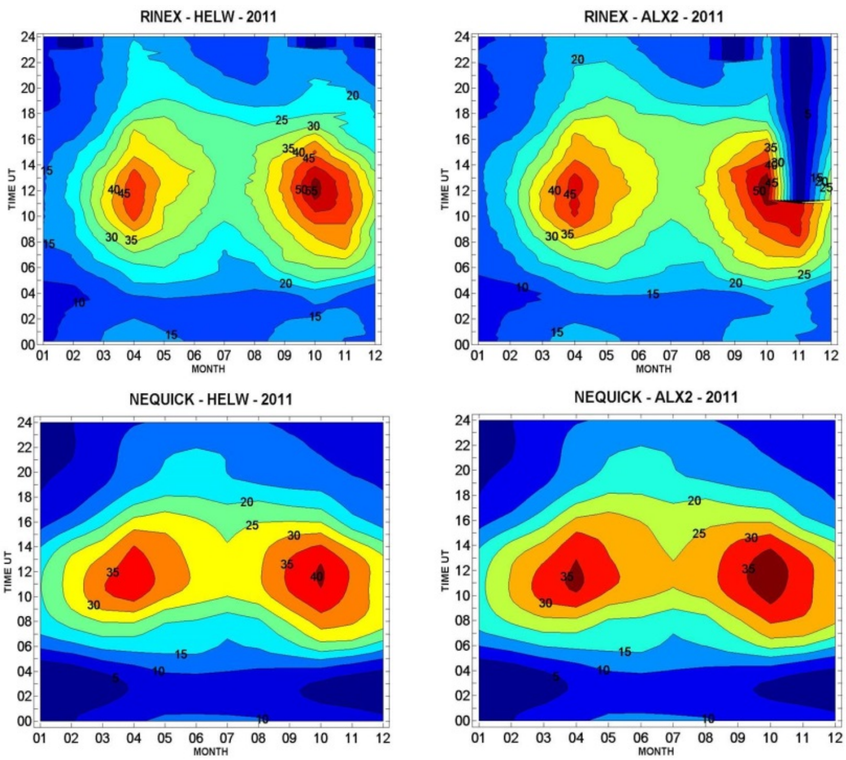

Figure 4. Contour map of VTEC measured and simulated data during the year 2011 at HELW and ALEX2 stations.

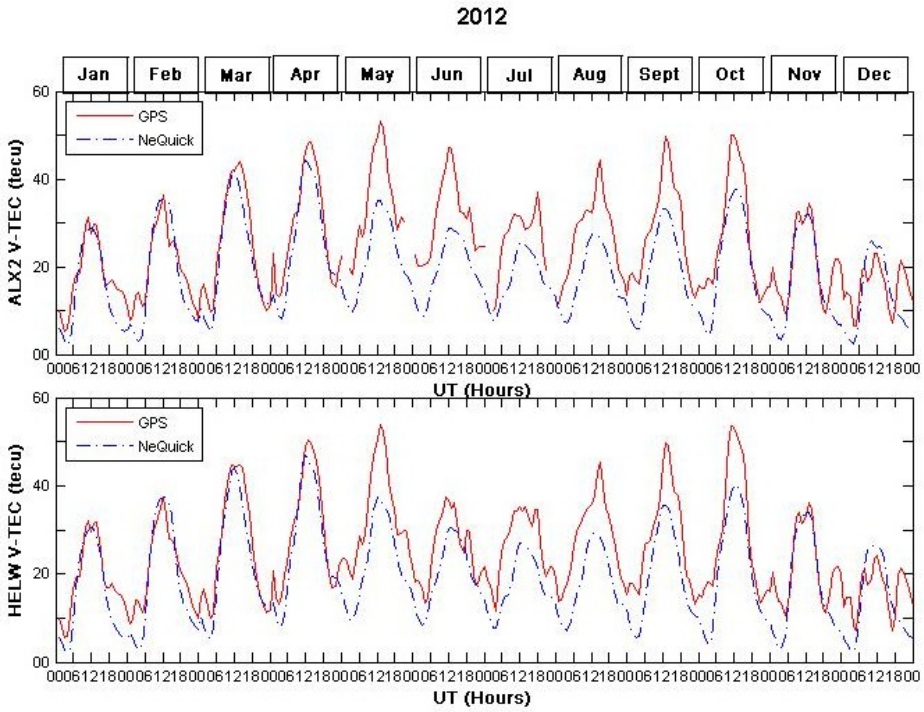

Figure 5. The monthly variations of the measured GPS-VTEC measured-(continuous red line) and the NeQuick simulated ones (dashed blue line) data taken from ALEX2 and HELW stations during the year 2012.

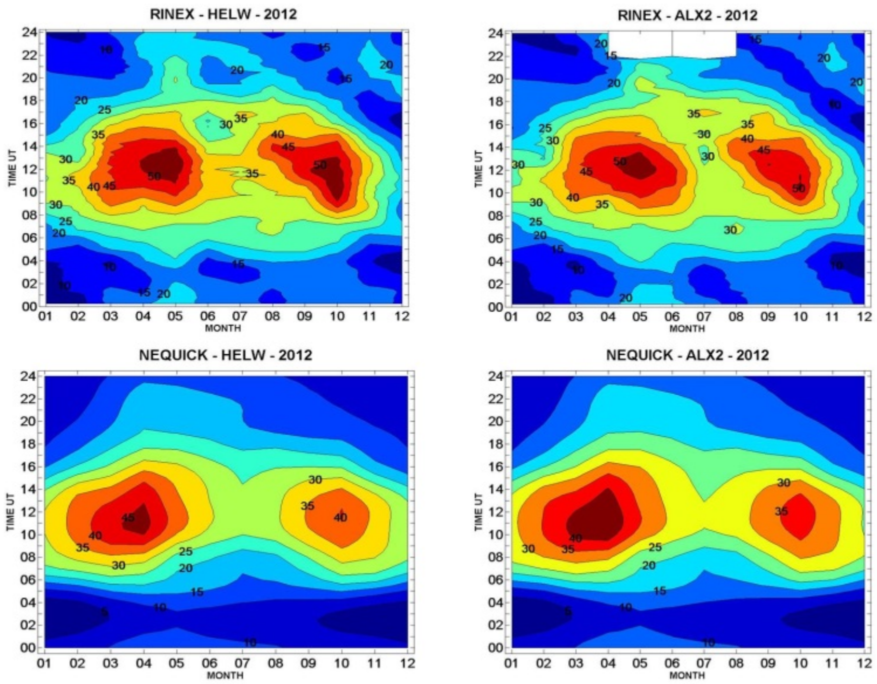

Figure 6. Contour map of VTEC measured and simulated data during the year 2012 at HELW and ALEX2 stations.

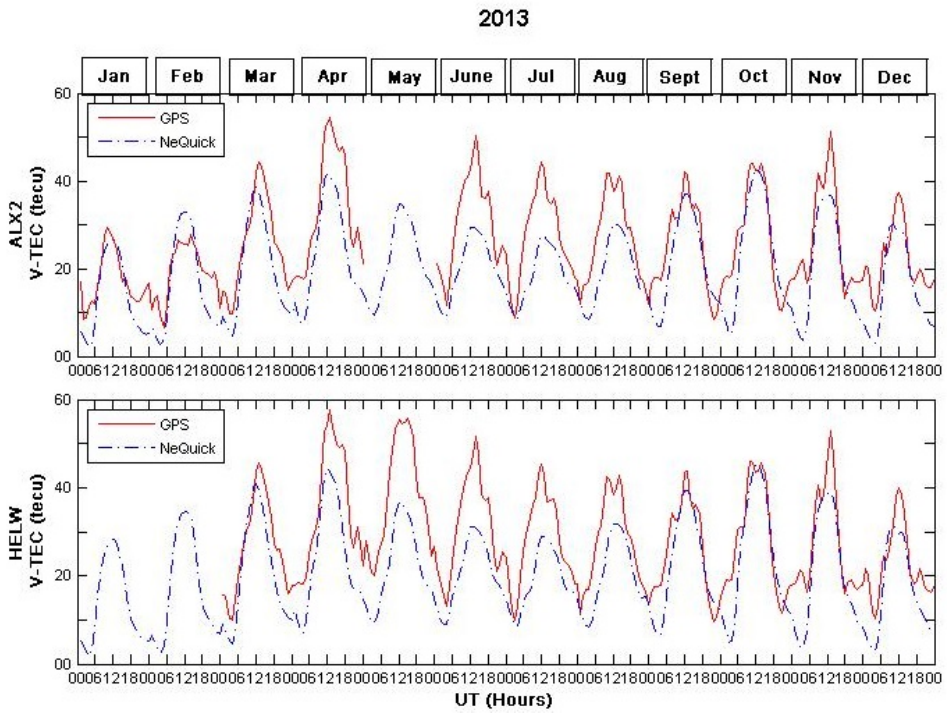

Figure 7. The monthly variations of the measured GPS-VTEC measured-(continuous red line) and the NeQuick simulated ones (dashed blue line) data taken from ALEX2 and HELW stations during the year 2013.

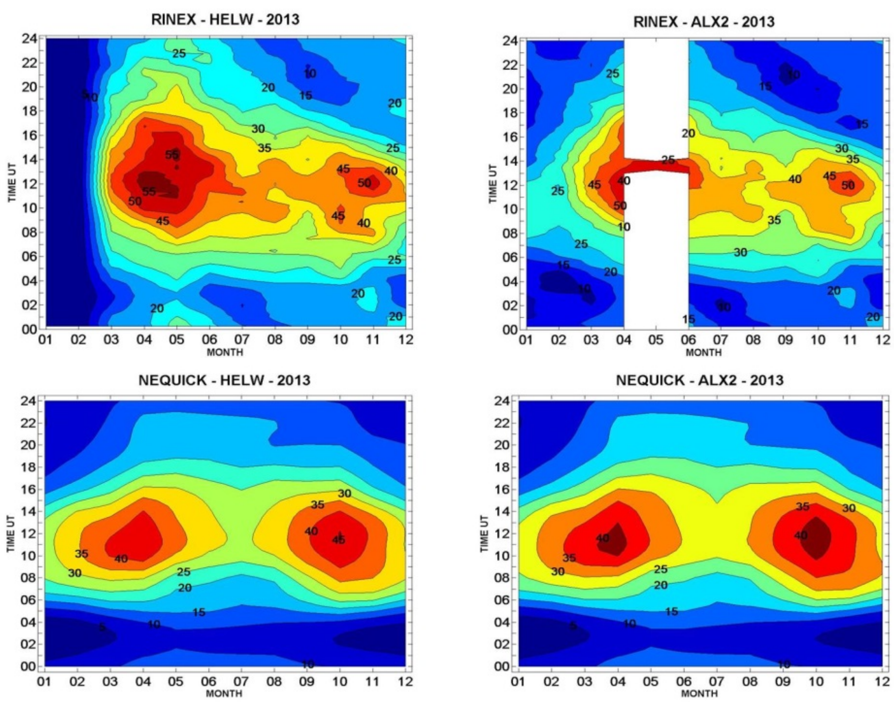

Figure 8. Contour map of VTEC measured and simulated data during the year 2013 at HELW and ALEX2 stations.

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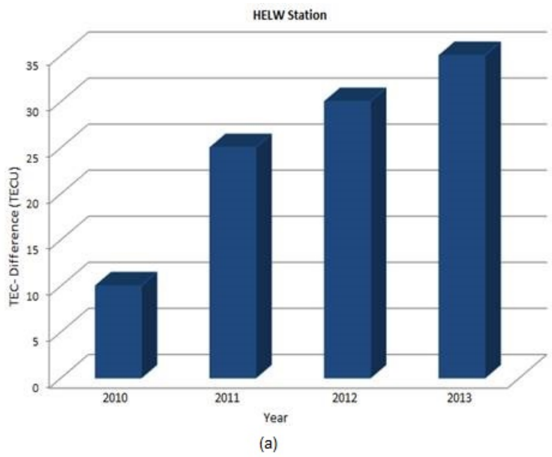
By comparing the experimental results derived from HELW and ALEX2 stations, there is harmony between their deviation values. This can be attributed to the small difference in latitude and practically at the same local time.

However, the experimental VTEC values at HELW may experience a small increasing than ALEX2. This is because the geomagnetic latitudes at HELW may be considered near to the northern crest of the equatorial anomaly. From the comparison figures, both the measured GPS-VTEC values and the simulated NeQuick ones show two daytime peaks appear mainly at the beginning of the two Equinox seasons. Tracking the difference between the measured and simulated VTEC through the monthly plots and the contour maps, an obvious increasing in the deviation appears as moving toward the maximum of the solar cycle.

The TEC values during the solar minimum year, 2010, show the best matching between the experimental and simulated results (Fig.1). The contour maps in Fig. 2 also confirm the above results as the values of the two equinox peaks are comparable. Fig. 3 shows the TEC monthly plots for 2011 which is higher than that in the previous year. A weighted difference appears between the measured and simulated TEC values at HELW and ALEX2, especially at the equinox months. The corresponding contour maps in Fig. 4 shows that the difference between the measured and simulates VTEC rises as moving to higher levels in the solar cycle. In 2012 (Fig. 5), the VTEC-GPS data is weightily overshooting the NeQuick simulated results at the whole of day in the summer and autumn with an average deviation of about 10 TECU. The measured GPS-TEC data shows 50 TECU peak at both vernal and autumn equinoxes at the noontime (Fig. 6). The NeQuick simulated results shows also TEC peaks but lower in value at the equinox and autumn. Fig. 7 displays the monthly variations of the GPS-VTEC which is almost higher than the simulated NeQuick results during the winter daytime. The higher deviation at the summer is greater than that in the previous years. Also, the peaks appeared in the NeQuick simulated results (Fig. 8) show high values in the vernal equinox and autumn respectively during the daytime at HELW and ALEX2 stations. These values being less than the GPS measured ones.



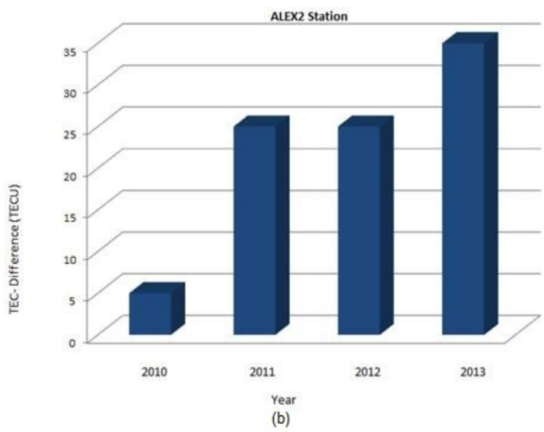


Figure 9. Average difference in TEC values between the GPS-measured and NeQuick-simulated electron density from 2010 to 2013 at (a) HELW and (b) ALEX2 stations.

There is always a difference between the experimental VTEC measurements and the simulated NeQuick ones. This difference being minimum during low solar activity, 2010, and then begin to ascending increase in a convenient way with the enhanced solar activity (Figure 9).

4. Conclusion

This paper provides a method to investigate the monthly/annual TEC variations in the low-mid latitude ionosphere and explore the sensitivity of NeQuick modeling TEC during solar activity variation. The NeQuick results show a good representation during the daytime at low solar activity (2010) in contrary with the nighttime. The observed behaviour of the ionospheric TEC manifest that the annual TEC contour maps show a remarkable seasonal variation. The TEC values on both GPS-receivers yield their maxima during the vernal and autumnal months. The TEC seasonal changes results from changes in the ratio of the concentration of atomic oxygen and molecular nitrogen (O/N2) in the F-region. In the equinoctial months, solar radiation is absorbed mainly by atomic oxygen. This is the reason for high values of TEC in the equinoxes [9]. The low values of TEC are observed in winter whereas high values are observed in equinox and summer.

It can be seen that both the two GPS observations yield similar tendencies in both TEC values and occurrence time. However, there is still a quite difference in TEC values at the two stations. This may be attributed to the different observing instruments employed.

The TEC behavior is practically the same at the two GPS stations due to the small difference in latitude between the two stations. But, the difference between the experimental and modeled values at HELW station shows higher values than the difference at ALEX2. Also, the maximum variation appears in the equinox and the minimum occurs in the summer.

In general, an obvious increasing difference between the experimental and modeled TEC values was appeared during the enhancing phase of the solar cycle which has a notable effect on the results.

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