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Research paper I Оригинални научни рад
DOI 10.7251/STP2215283T
ISSN 2566-4484

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COMPARISON OF IRI-2016 AND NEQUICK MODELS OF THE IONOSPHERE OVER THE BALKAN PENINSULA DURING THE YEAR 2019

Abstract

In this paper, a comparative study of the total vertical electron content (VTEC) calculated using the IRI-2016 and NeQuick2 models were performed. The research was done for the days of maximum solar activity in 2019, with data from seven IGS GNNS stations in the region of the Balkan Peninsula. The results show that both models agree quite well with the observed VTEC values obtained from GNSS measurements at all stations, although with some offset observed during several days at different times. The IRI-2016 model performed better than the NeQuick2 model most of the days and stations for which the NeQuick model overestimates the GNSS VTEC. The results show that the Neckick model gives better quality values in some cases, but for isolated instances.

Keywords: ionosphere, GNSS, IRI-2016, NeQuick

ПОРЕЂЕЊЕ IRI-2016 И NEQUICK МОДЕЛА ЈОНОФЕРЕ ИЗНАД БАЛКАНСКОГ ПОЛУОСТРВА ТОКОМ 2019. ГОДИНЕ

Сажетак

У овом раду вршена је упоредна студија вредности укупног вертикалног садржаја електрона (VTEC) срачунатог коришћењем IRI-2016 и NeQuick2 модела. Истраживање је рађено за дане максималне соларне активности током 2019. године са подацима са седам ИГС ГНСС станица у региону Балканског полуострва. Резултати показују да се оба модела прилично добро слажу са вредностима VTEC добијеним из ГНСС мерења на свим станицама, иако са извесним неслагањима уоченим током неколико дана у различитим временским интервалима. Модел IRI-2016 је показао боље перфрормансе од NeQuick2 модела за већину тестираних периода и већину станица за које NeQuick2 прецењује ГНСС VTEC vrednosti. Резултати показују да NeQuick2 модел даје вредности бољег квалитета, али само у ограниченом броју случајева.

Кључне ријечи: јоносфера, ГНСС, IRI-2016, NeQuick

1. INTRODUCTION

The ionosphere is an area of the Earth's atmosphere and extends at an altitude of about 60 km to 2000 km. According to the distribution of electron density depending on altitude, the ionosphere can be divided into four layers D (60-90 km), E (90-140 km), F1 (140-210 km), and F2 (over 210 km). The significant presence of electrons in the ionosphere directly affects electromagnetic waves by changing their direction and speed and adversely affects radio communication and navigation, aviation, and the Global Navigation Satellite System (GNSS).

Therefore, it is necessary to determine the spatial distribution of electrons in the ionosphere precisely. One of the important parameters used to characterize the ionosphere is the Total Electron Content (TEC) defined by the number of electrons integrated between two points along a tube of unit cross-sectional area. TEC is expressed in TECU units, where 1 TECU = 10^{16} electrons/m^2. Based on the multitude of ionospheric data from GNSS satellites, along with the need for accurate navigation, various models of the ionosphere have been established that provide predictions of ionospheric TEC where actual data are absent. In this context, the comparison of the performance of two empirical models to predict of ionosphere parameters, with an accent on TEC values, is the subject of this paper. These are the International Reference Ionosphere (IRI) and NeQuick models. GNSS measurements were used to validate the IRI and NeQuick models, and VTEC values were calculated from RINEX (Receiver Independent Exchange) files for seven IGS stations in the Balkan Peninsula.

The International Reference Ionosphere (IRI) is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). In the late 1960s, a working group was formed to establish a global empirical model based on all available data sources at the time [1]. Since 1978 [2], when the model was implemented, several improved versions have been released, including IRI-1990, IRI-2000, IRI 2007 and IRI-2012. IRI-2016 is the current version. The IRI model is based on a large amount of ground-based and space-based observational data, mainly from satellites, incoherent scattering radars, and altimeters [3]. The input variables of the IRI model include date, coordinates, solar index, ionospheric index, and magnetic index. The height range of the electron density is 65–2000 km day time and 80–2000 km night time. The model provides ionospheric variables, e.g., monthly average electron density, electron temperature, ion temperature, ion composition, etc. [3].

The NeQuick model is a time-dependent, three-dimensional ionospheric electron density model. This model was developed at the International Center for Theoretical Physics (ICTP) in Trieste, Italy, and at the University of Graz, Austria for the Galileo satellite system to calculate ionospheric delay corrections for single-frequency users [4]. The model is divided into lower and upper models. Input variables are geocentric latitude, geocentric length, altitude, universal time (UT) and solar activity (given a monthly mean sunspots number R12 or 10.7 cm solar radio flux of F10.7). The NeQuick provides services to evaluate the electron density along any ground to satellite, straight line ray path and the corresponding TEC by numerical integration. The NeQuick model includes two versions of NeQuick1 and NeQuick2 [5]. The NeQuick2 version was used in this paper.

Many authors have made performance comparisons of the ionospheric models so far, both for the global and local areas. The accuracy of the model during the period of calm and medium solar activity at the global level [6], in the Antarctic region [7], at equatorial and low latitudes [8], etc. was examined. In this context, this paper aims to analyze the performance of both ionosphere models by focusing on the Balkans. To achieve that, a couple of stations in the area of the Balkan Peninsula were chosen for the period during 2019 for the days for which increased solar activity was observed.

2. DATA AND METHODOLOGY

2.1. SOLAR AND MAGNETIC CONDITIONS

Changes in the ionosphere, and therefore TEC's value, largely depend on geomagnetic and solar activity.

The essential parameter of geomagnetic activity is the *Ap* index. The *Ap*-index provides a daily average level for planetary magnetic activity, with units of 2nT. Definitive values of *Ap* are provided by GeoForschungsZentrum (GFZ) Potsdam, Adolf-Schmidt-Observatorium für Geomagnetismus, Niemegk, Germany on behalf of the International Service of Geomagnetic Indices (ISGI) of the International Association of Geomagnetism and Aeronomy (IAGA).

The sunspot number index *Rn* measures the area of solar surface covered by spots. As the number of spots increases and their magnetic complexity grows, they become likely sources of sizeable eruptive energy releases known as solar flares, directly affecting the ionosphere. Besides daily, monthly, and yearly averages, a 12-month running mean value, R_{12} *(Rn)*, is calculated. Since 1981 an International Sunspot Number *Ri* been derived by A. Koeckelenbergh at the World Data Center C for Sunspots in Brussels, Belgium. Analyzing the long record of observations, it has been found that the cycle period varies from ten to 12 years with a mean of 11 years. Cycles are numbered chronologically. Solar Cycle 25 began in December 2019, so the year 2019 belongs to cycle 24. The 10.7 cm solar radio flux, or $F_{10.7}$ is, along with sunspot number, one of the most widely used indices of solar activity. It measures the noise level generated by the sun at a wavelength of 10.7 cm at the Earth's orbit. The global daily value of this index is measured at local noon at the Dominion Radio Astrophysical Observatory (DRAO) in Penticton, Canada.

Figure 1 shows the parameters *Ap*, *Rn* and *F10.7* for the year 2019.

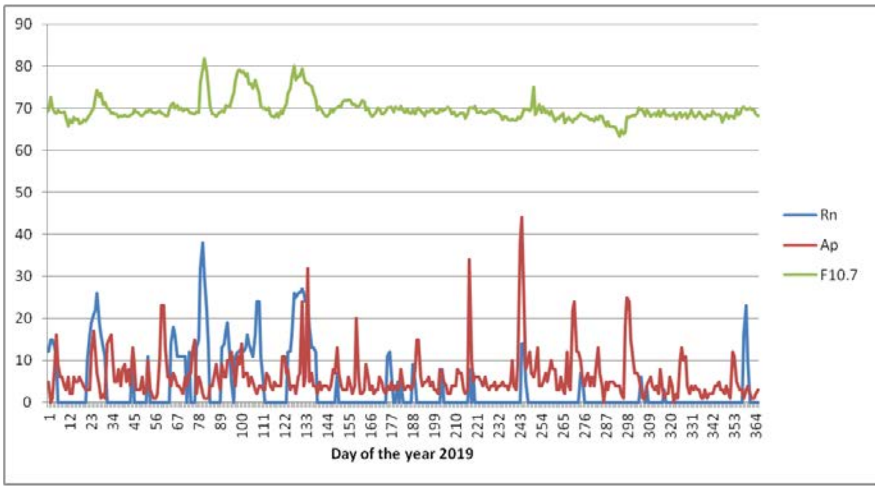

Figure 1. *Parameters Ap, Rn and F10.7 for year 2019*

2.2. DATA DESCRIPTION

The observational data used in this study were the dual-frequency observational data from GNSS stations in the Balkan Peninsula and the surrounding areas. These stations include five IGS stations in the Balkans and two stations outside, of which one is in Austria and the other in Hungary. Stations in Austria and Hungary were chosen to cover the northern part of the peninsula. The distribution of all these stations is shown in Figure 2 and the detailed coordinates are provided in Table 1.

Figure 2. *Distribution of GNSS points*

The observational data were collected in January, March, April, Maj, September and December 2019, for days for which enhanced solar and geomagnetic activity has been observed. The dates for which testing was performed are shown in Table 2.

Table 1. Coordinates of IGS GNSS stations considered in this study

Station	Latitude	Longitude	Height
GRAZ00AUT	47.067	15.493	538.3
PENC00HUN	47.790	19.282	291.7
BUCU00ROU	44.464	26.126	143.2
SOFI00BGR	42.556	23.395	1119.6
ORID00MKD	41.127	20.794	773.0
DYNG00GRC	38.079	23.932	510.6
ISTA00TUR	41.104	29.019	147.2

Table 2. Days of the month for which the data were collected

Month	Day of the month
January	24, 25
March	21, 22
April	18, 19
May	11, 13, 14
September	1
December	25

2.3. GNSS VTEC

The RINEX (Receiver Independent Exchange) format observation files obtained for the years 2019 from seven GNSS receivers stationed at different locations (Table1). To get the $\text{VTEC}_{\text{GNSS}}$, RINEX files are processed using the GPS-TEC analysis application software version 3 developed by Gopi Seemala of the Institute for Scientific Research, Boston College, USA [9].

This software calculates GNSS TEC based on the principle that the dual frequency GNSS receivers use L_1 (1575.42 MHz) and L_2 (1227.60 MHz) to derive TEC using differential delay technique. The ionospheric time delay at the L1 carrier frequency of f_1 is:

$$t_1 = 40.3\left(\frac{TEC}{C \cdot f_1^2}\right) \tag{1}$$

where C is the speed of light. The difference in the time delay between L_1 and L_2 frequencies, is given by

$$\Delta t_1 = \left(\frac{40.3}{C}\right) \times \left(\frac{TEC}{\frac{1}{f_1^2} - \frac{1}{f_2^2}}\right) \tag{2}$$

where $\Delta t = t_2 - t_1$. The above calculated TEC is slant TEC (STEC), and the accuracy of absolute TEC measurements can be improved with differential phase measurements. Vertical TEC (VTEC) can be calculated as:

$$VTEC = \frac{STEC - b_r - b_s}{S(E)} \tag{3}$$

where b_r is the receiver bias, b_S is the satellite bias and $S(E)$ is mapping function, which is defined as

$$S(E) = \frac{1}{cos(Z)} = \left[1 - \left(\frac{R_E \times cos(E)}{R_E + h_s}\right)^2\right]^{-\frac{1}{2}} \tag{4}$$

where Z is the zenith angle of the satellite as seen from the observing station, R_E is the radius of the Earth, E is the elevation angle, and h_s is the ionospheric effective height above the Earth's surface which is taken as 350 km.

2.4. IRI – 2016

The IRI model has been developed to specification ionospheric parameters supported by the Committee on Space Research and the International Union of Radio Science (URSI). A team of international experts continuously improves it as the new data becomes available. IRI model describes the electron density, temperature, composition, and TEC for a given location, time, and date. The version of this model IRI-2016 includes two new model options for the F2 peak height hmF2 and a better representation of topside ion densities at very low and high solar activities. In addition, a number of minor changes were made concerning the use of solar indices and the speedup of the computer program. In this paper, the calculation of daily $\mathrm{VTEC_{IRI\text{-}2016}}$ values on a sample of 1 min was performed.

A detailed description of the IRI-R016 can be found in [3].

2.5. NEQUICK2

The NeQuick model is a time-dependent, three-dimensional ionospheric electron density model.

He reproduces the electron density distribution in the ionosphere analytically based on a model introduced by Di Giovanni and Radicella (DGR model) [9]. Recently, much effort has been made to improve the existing model, given the increasing data availability. Therefore, versions of the NeQuick2 model were obtained. The changes that have been made are related to the parameter for defining the bottom side and topside. Five Semi-Epstein layers were used with modeled thickness parameter for description of the ionosphere's electron density above 90 km and up to a peak of the F2 layer. A one-minute calculation period was chosen to obtain the $\mathrm{VTEC_{NeQuick}}$ value in this paper. Details of the NeQuick2 model analytical formulation can be found in [10].

2.6. COMPARISON OF DIFFERENT MODELS

To investigate the accuracy of the IRI-2016 and NeQuick2, in this study, the difference and its absolute value between the $\mathrm{VTEC_{GNSS}}$ and the modeling VTEC ($\mathrm{VTEC_{IRI\text{-}2016}}$ or $\mathrm{VTEC_{NeQuick}}$) were computed, as shown in Equation (5) and (6).

$$\Delta\mathrm{VTEC_{IRI-2016}} = \mathrm{VTEC_{IRI-2016}} - \mathrm{VTEC_{GNSS}} \tag{5}$$

$$\Delta\mathrm{VTEC_{NeQuick2}} = \mathrm{VTEC_{NeQuick2}} - \mathrm{VTEC_{GNSS}} \tag{6}$$

We compute the Root Mean Square Deviation (RMSD) of the IRI-2016, NeQuick2 and the of both models using Equations (7) and (8)

$$RMS\Delta = \sqrt{\frac{\sum_1^n (\Delta VTEC_{IRI-2016})^2}{n}} \tag{7}$$

$$RMS\Delta = \sqrt{\frac{\sum_1^n \left(\Delta VTEC_{NeQuic2}\right)^2}{n}} \tag{8}$$

where n is the number of data.

3. RESULTS AND ANALYSIS

Daily VTEC variations from the GNSS, IRI-2016 and NeQuick2 models were performed for all seven stations during typical 2019 days. These are the days for which increased solar activity was observed concerning the indices *Ap*, *Rn* and *F*10.7. The results are presented in Figures 3, 4, 5 and 6. Green curves represent daily values of VTEC variations measured by GNSS, red curves represent NeQuick2 variations of VTEC derived from the model, and blue curves represent VTEC variations based on the IRI-2016 model. From all these diagrams, it is clear that the daily variation of VTEC shows lower values at night, with a gradual increase in the morning, so that the maximum values appear between 10 and 14 (UT) hours. After that, the VTEC values gradually decrease towards the evening hours, where the minimum occurs between 1 and 4 hours (UT). The maximum values of VTEC were detected on January 24, 2019. and May 25, 2019. Values amount from 8 to 18 TECU for 11.05. (12 UT) and from 9 to 14 TECU for 14.05. (10 UT). For the day 25.12. which has the most negligible fluctuations in the ionosphere of the selected days, all ststions have daily VTEC variations ranging from 1.5 to 7.5 TECU (Figure 4).

The daily TEC variations derived from the IRI-2016 and NeQuick2 models follow all the above characteristics with a difference of about 0.5 to 7 units of total electron content (TECU) (1 TECU = 10^{16}el/m^2) compared to $\mathrm{VTEC_{GNSS}}$. Figures 7, 8 and 9 show the differences between the modeled and GNSS values of VTEC at all seven stations for the selected days and time during 2019. Data were selected at moments when the maximum VTEC values were obtained. The most significant differences are observed during the maximum of daily solar activity in the period between 9 and 14 UT for all stations and both models. The differences go up to 8 TECU.

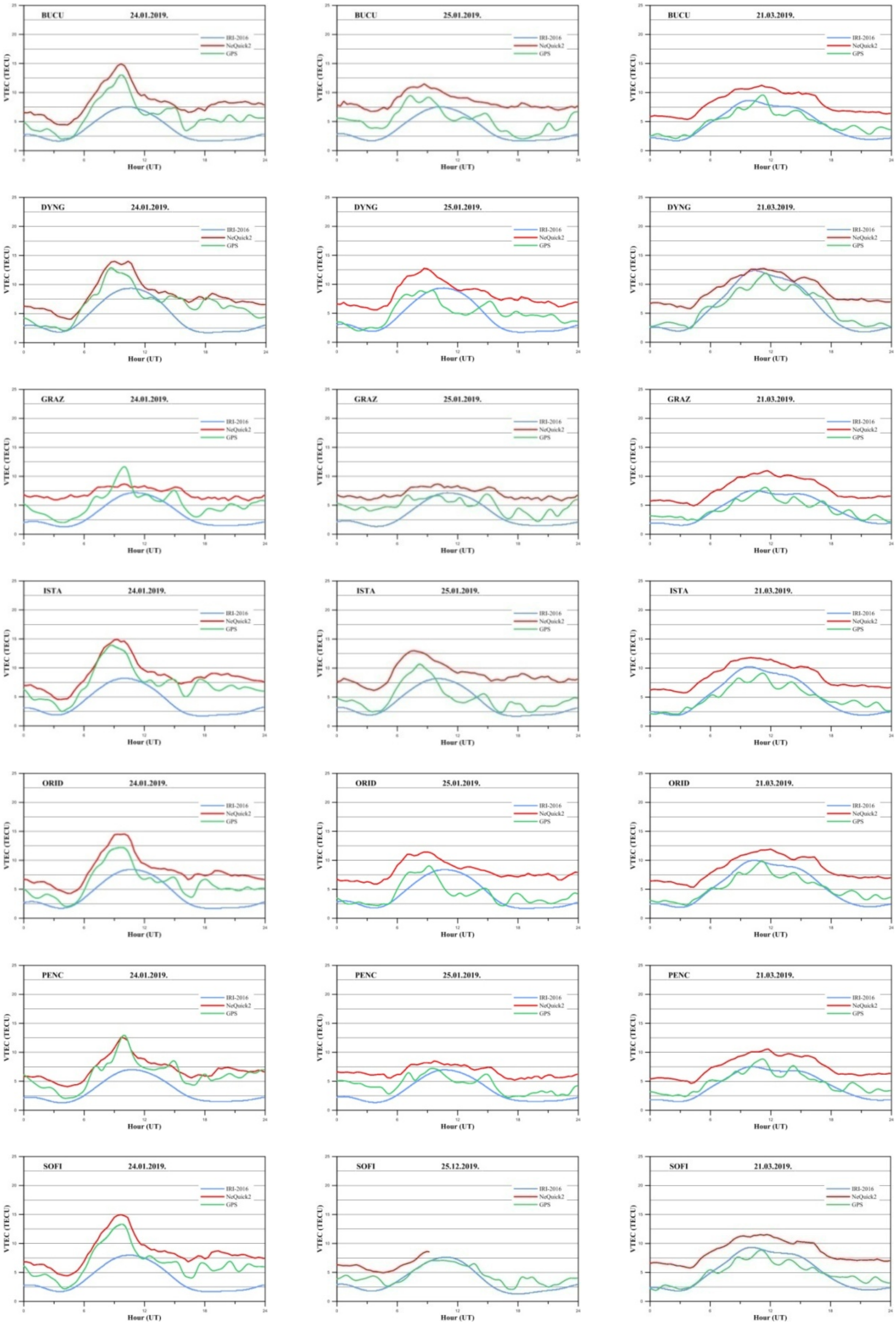

Figure 3. *Daily variation of VTEC values for GNSS (green line), IRI-2016 (blue line) and NeQuick2 (red line) during 24.01., 25.01. and 21.03. 2019.*

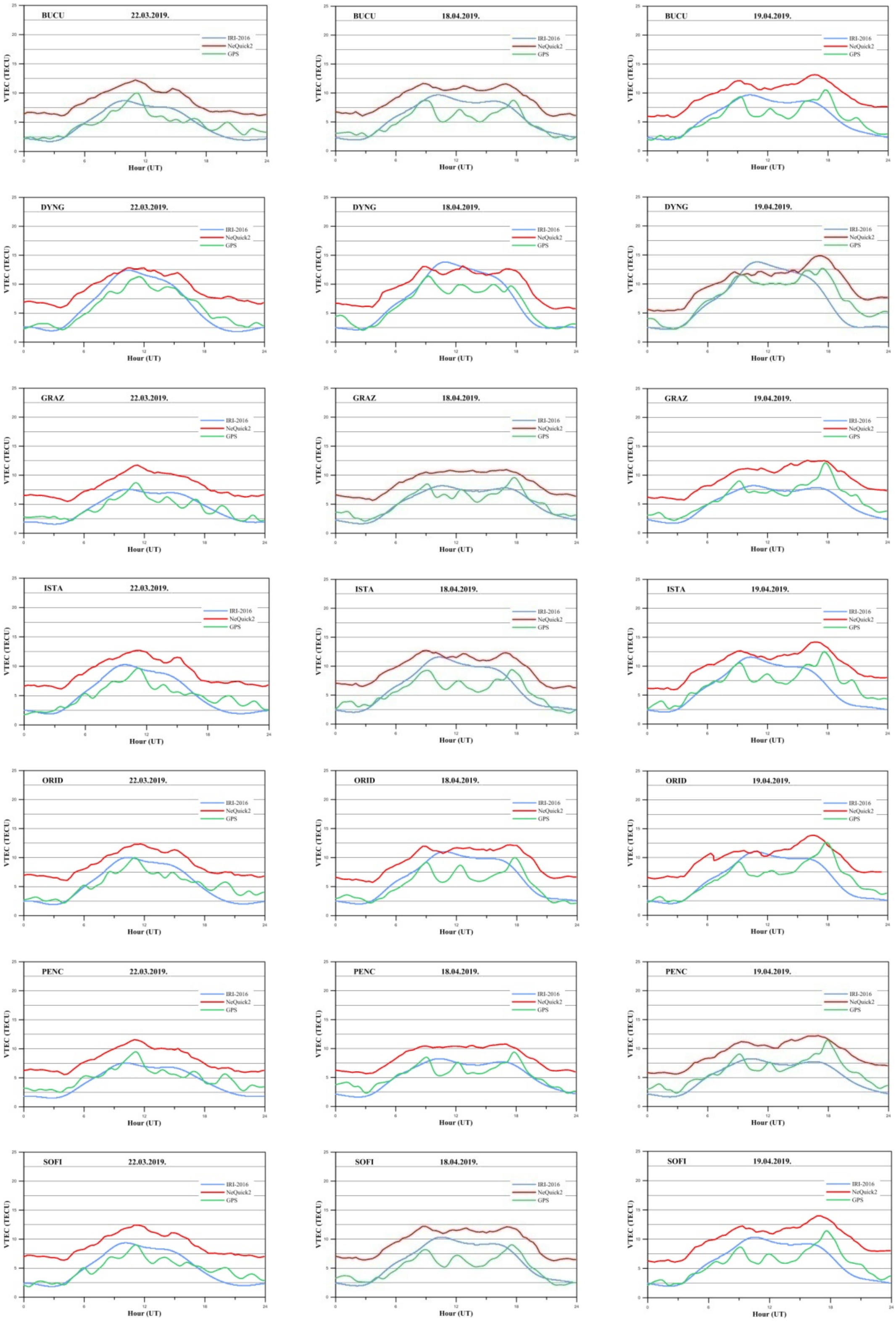

Figure 4. *Daily variation of VTEC values for GNSS (green line), IRI-2016 (blue line) and NeQuick2 (red line) during 22.03., 18.04. and 19.04. 2019.*

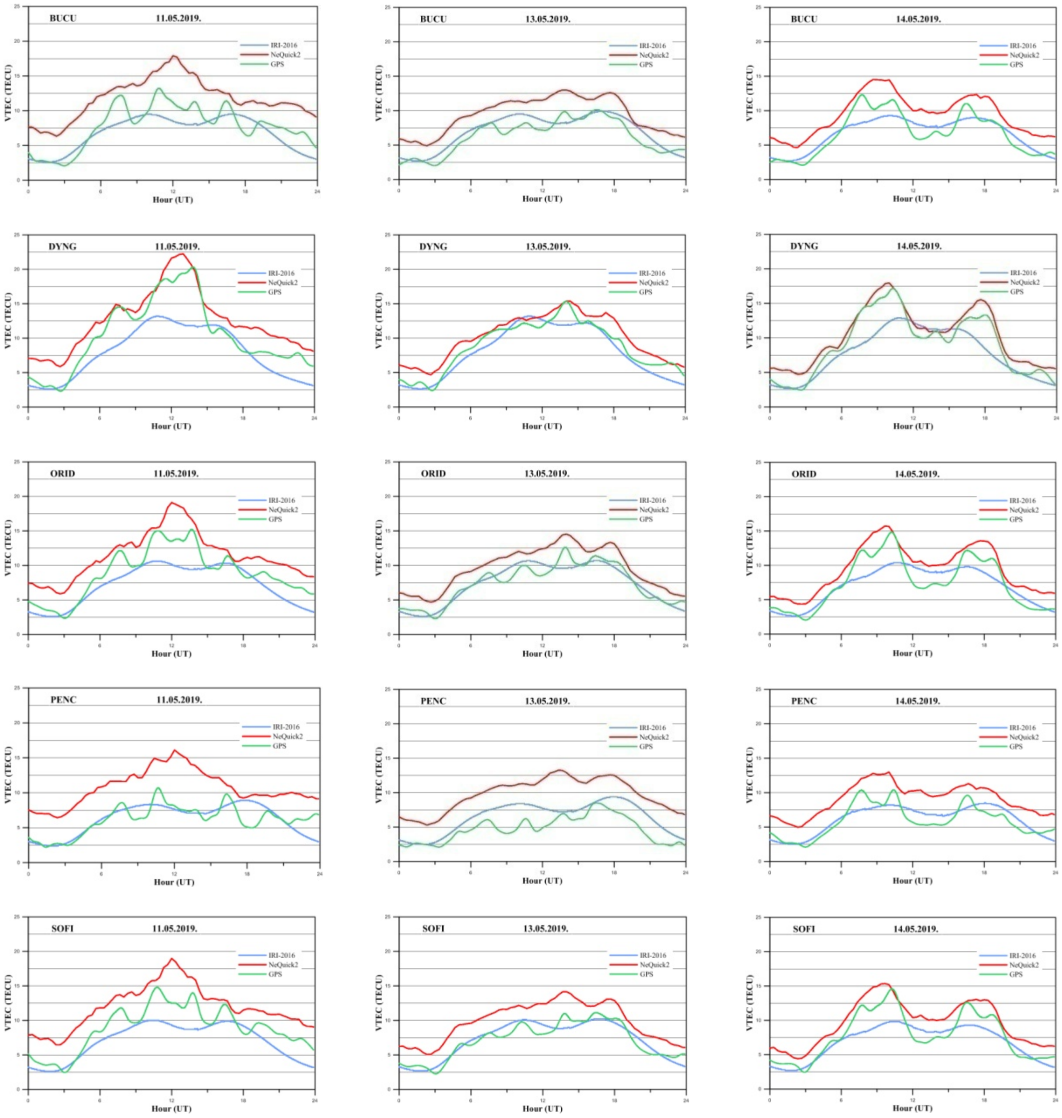

Figure 5. *Daily variation of VTEC values for GNSS (green line), IRI-2016 (blue line) and NeQuick2 (red line) during 11.05., 13.05. and 14.05. 2019*

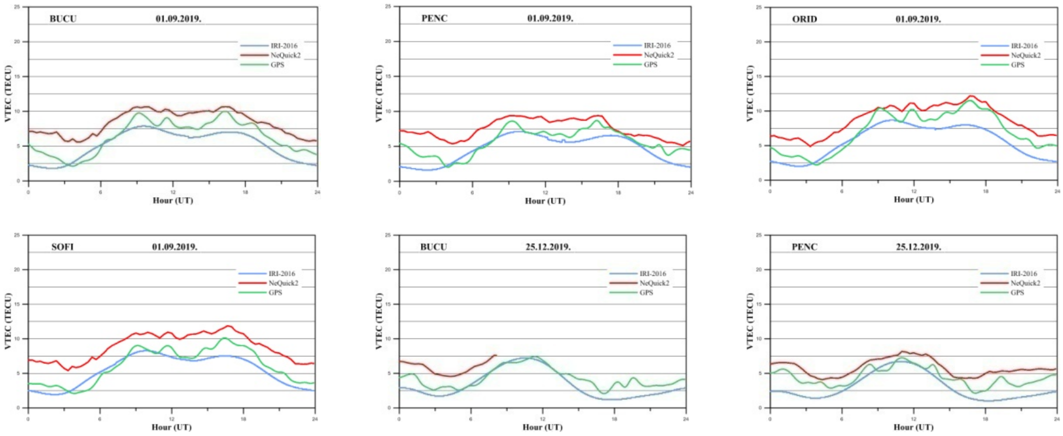

Figure 6. *Daily variation of VTEC values for GNSS (green line), IRI-2012 (blue line) and NeQuick2 (red line) during 01.09. and 25.12. 2019.*

The VTEC values derived from the IRI-2016 and NeQuick model show more significant differences for the days of intensified solar activity, for example, during April and May 2019, while during other periods, they follow the $VTEC_{GNSS}$ values quite well. The VTEC values from these two models are almost similar for all stations during all test periods. It is interesting to note that for the day 24.01. generally, the VTEC values derived from the NeKuick2 model and obtained from GNSS measurements match quite well (maximum difference of about 2.5 TECU at all locations. In comparison, the values from the IRI-2016 model deviate significantly (about 7 TECU). Also, it was noticed that the values of $VTEC_{GNSS}$ and $VTEC_{IRI-2016}$ match quite well for all other days, and that the values of $VTEC_{NeQuick}$ generally for all days and all stations (except for January 24) have higher values than VTEC $_{IRI-2016}$ and $VTEC_{GNSS}$.

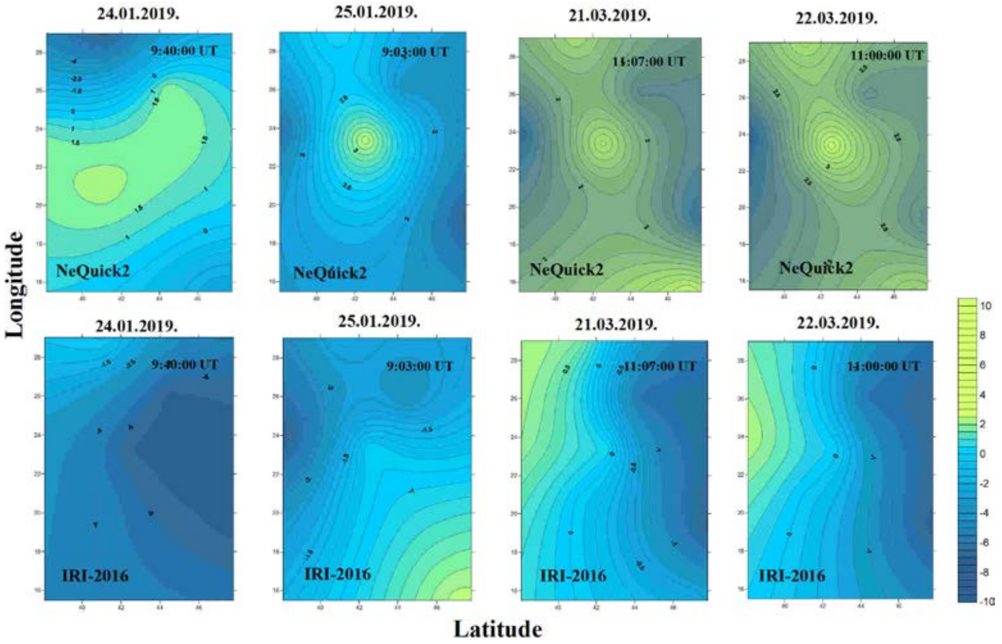

Figure 7. *Distribution of differences between the $VTEC_{GNSS}$ and modeled VTEC ($VTEC_{IRI-2016}$ and $VTEC_{NeQuick2}$) during 24.01., 25.01., 21.03. and 22.03. 2019.*

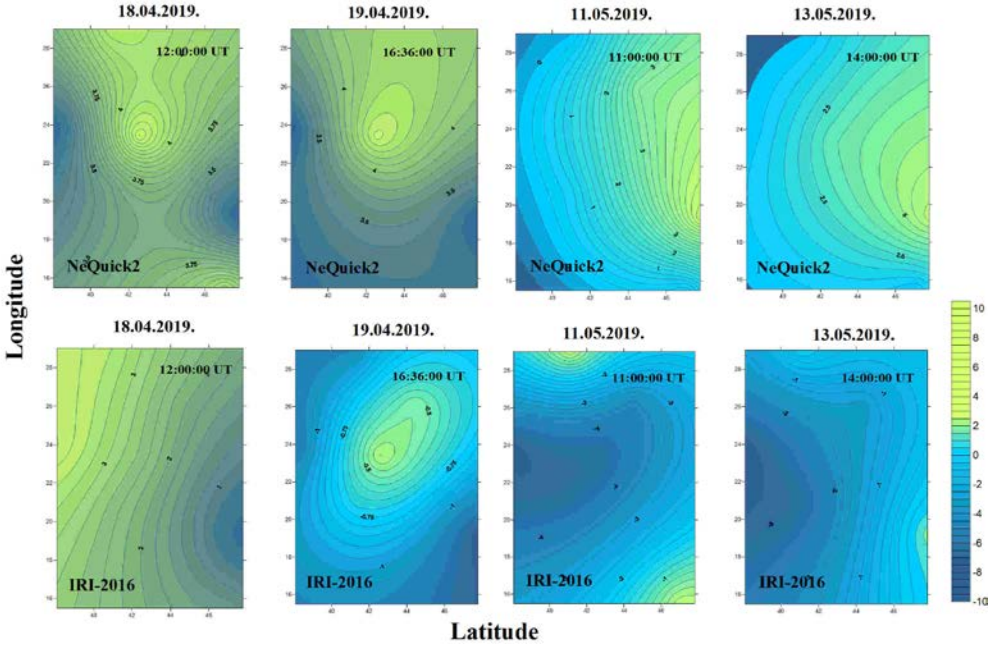

Figure 8. *Distribution of differences between the $VTEC_{GNSS}$ and modeled VTEC ($VTEC_{IRI-2016}$ and $VTEC_{NeQuick2}$) during 18.04.,19.04., 11.05. and 13.05. 2019.*

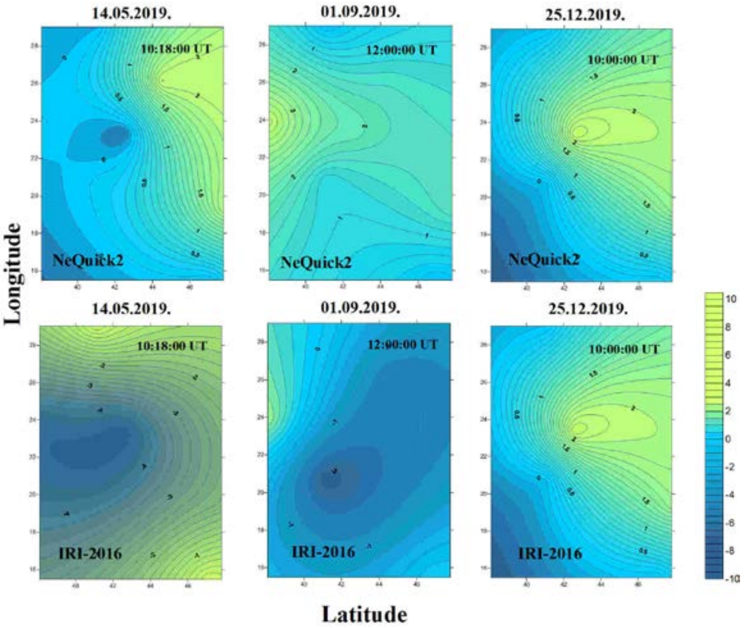

Figure 9. *Distribution of differences between the VTEC$_{GNSS}$ and modeled VTEC (VTEC$_{IRI-2016}$ and VTEC$_{NeQuick2}$) during 14.05.,01.09., and 25.12. 2019.*

Table 3 presents the estimated RMSE VTEC in TECU unit for seven stations, considering the results of the eleven processed days of year 2019. and the two ionospheric approaches: IRI-2016 and NeQuick2. Analyzing the data, it can be noticed that both models have approximate values and that their performance is therefore satisfactory. Although, it can be concluded that IRI-2016 gives slightly better results, because the value of RMSD is not higher than 2.03 for any station.

Table 3. RMSD of the VTEC$_{IRI-2016}$ and VTEC$_{NeQuick2}$ values from the different stations during 2019

Station	Model	Number of valus	Min (TECU)	Max (TECU)	RMSD (TECU)
BUCU	IRI-2016	15774	-5.6	4.62	1.82
	NeQuick2	14889	0.28	7.05	1.09
DYNG	IRI-2016	15840	-8.50	5.44	2.01
	NeQuick2	15840	-8.80	4.62	2.32
GRAZ	IRI-2016	8640	-5.99	2.40	1.42
	NeQuick2	8640	-3.00	5.47	1.17
ISTA	IRI-2016	11517	-6.37	5.48	2.03
	NeQuick2	11517	-10.5	9.08	3.82
ORID	IRI-2016	15799	-5.80	5.26	1.77
	NeQuick2	15799	-7.18	5.61	2.14
PENC	IRI-2016	15837	-6.94	4.14	1.63
	NeQuick2	15837	-1.26	7.98	1.49
SOFI	IRI-2016	14949	-5.97	5.12	1.81
	NeQuick2	14949	-0.51	6.47	1.23

4. CONCLUSIONS

In this paper, we have investigated the performance of the IRI- 2016 and NeQuick2 model to predict the GNSS VTEC for seven selected GNSS stations located in the Balkan peninsula during 2019. The results from this study show that the VTEC predicted by both models agrees quite well with the observed GNSS VTEC measurements, although with some offset observed during several days at different times. The IRI-2016 model performed better than the NeQuick2 model most of the days and stations for which the NeQuick model overestimates the GNSS VTEC. The results show that the Neckick model gives better quality values in some cases, but this does not apply to all days or to all stations. Since GNSS VTEC are greater during equinoxes than in the solstice seasons and since the differences in VTEC values from both models depend on local time, latitude, and solar activity, it is necessary to take these parameters into account when modeling VTEC values. To obtain a realistic evaluation of the quality of these two models, it is necessary to perform further analyzes. The plan is to expand the research to more time periods including days of intensified and days of quiet solar activity over several years, and to consider the influence of station latitude.

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