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Performance of the NeQuick 2 model during the geomagnetic storm

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ABSTRACT
The aim of this study is to evaluate the performance of NeQuick 2 model during geomagnetic storm process. For this purpose, vertical total electron content (VTEC) values obtained from NeQuick 2 model and GPS (Global Positioning System) receiver were compared for five stations selected from 5 different latitude regions during 05-09 September 2017. Comparison was made by correlation, root mean square error (RMSE) and difference taking methods. The variation of VTEC values obtained by NeQuick 2 and GPS is generally similar, although there are phase shifts and amplitude differences. The maximum correlation was observed in the equator region on the quiet days before the storm (September 5-6), but the correlation coefficient decreased as it moved away from the equator. The maximum correlation coefficient was calculated at the mid-latitude of the southern hemisphere during the initial, main and return phases of the storm. In addition, the lowest correlation was determined at high latitudes of the northern hemisphere. At all stations (except NYAL station on 05, 07, 08 / 09/2017), the maximum value of the calculated difference is smaller than the minimum value. When the GPS VTEC values are higher than the NeQuick 2 model values, the difference is generally low, on the contrary when the NeQuick 2 model values are greater than the GPS VTEC values, the difference is quite large. This shows that the NeQuick 2 model generally overestimates the TEC values.
Keywords: Geomagnetic storm, GPS TEC, NeQuick 2 model

Jeomanyetik fırtına süresince NeQuick 2 modelin performansı

ÖZ
Bu çalışmanın amacı, NeQuick 2 modelinin jeomanyetik fırtına sürecinde performansını değerlendirmektir. Bu amaçla, NeQuick 2 modelinden ve GPS alıcısından elde edilen dikey toplam elektron içeriği (VTEC) değerleri 05-09 Eylül 2017 tarihleri arasında 5 farklı enlem bölgesinden seçilen beş istasyon için karşılaştırıldı. Karşılaştırma korelasyon, kök ortalama kare hatası (RMSE) ve fark alma yöntemleri ile yapıldı. NeQuick 2 ve GPS tarafından elde edilen TEC değerlerinin değişimi, faz kaymaları ve genlik farkları olmasına rağmen, genellikle benzerdir. Maksimum korelasyon fırtına öncesi sakin günlerde ekvator bölgesinde gözlenirken (5-6 Eylül) ekvatordan uzaklaştıkça korelasyon katsayısı azalmıştır. Maksimum korelasyon katsayısı fırtınanın başlangıç, ana ve dönüş evrelerinde güney yarımkürenin orta enleminde hesaplanmıştır. Ek olarak, en düşük korelasyon kuzey yarımkürenin yüksek enlemlerinde belirlendi. Tüm istasyonlarda (05, 07, 08 / 09/2017 günlerinde NYAL istasyonu hariç) hesaplanan farkın maksimum değeri minimum değerden daha küçüktür. GPS VTEC değerlerinin NeQuick 2 model değerlerinden daha yüksek olduğu durumlarda, fark genellikle düşüktür, aksine NeQuick 2 model değerleri GPS VTEC değerlerinden daha büyük olduğunda, fark oldukça büyüktür. Bu durum, NeQuick 2 modelinin genellikle TEC değerlerini abarttığını göstermektedir.

Anahtar Kelimeler: GPS-TEC, Jeomanyetik fırtına, NeQuick 2 Model

INTRODUCTION

NeQuick is a three-dimensional, time-dependent ionospheric electron density model designed specifically for trans-ionospheric applications, which enables the calculation of the electron concentration at any given location in the ionosphere and the total electron content (TEC) along the beam path by numerical integration from any location to the satellite. The latest version of this model is NeQuick 2 [1]. Modeling and estimation of time and space-dependent changes in TEC, a critical quantity defining ionosphere and its variability, is of important for the investigation of the physical change of the ionosphere and for applications related to ionosphere [2]. Numerous studies have been conducted on the determination of ionospheric parameters using empirical models that can define the general state of the ionosphere without the need for real data. Some of these studies include ionosphere experimental models such as Klobuchar, NeQuick, Standard Plasmasphere Ionosphere Model (SPIM) and International Reference Ionosphere (IRI) [3]. NeQuick was first developed based on the G, Di Giovanni and S.M. Radicella (DGR) profiler (proposed

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by [4] and hence the name DGR), and then modified by [5]. A new version of NeQuick (NeQuick 2) is a modified subsection introduced by [6], [7] and [8]. NeQuick 2 model is appreciated for its improved performance in predicting the upper ionosphere, and as a result in the 2007 and later versions of the IRI model have been used the NeQuick's top formulation and adopted the most mature of the different recommendations for calculating the upper part of the IRI electron density profile [9-11]. NeQuick 2 model's prediction performance has been evaluated by many researchers in recent years. For example, Okoh et al. conducted a climatic assessment of the global navigation satellite system (GNSS) observations of NeQuick 2 and IRI-Plas models [12]. Ezquer et al. using vertical total electron content (VTEC) measurements from GPS satellite signals, analyzed the performances of NeQuick 2 and IRI Plas models to predict VTEC in the low latitude and South American sector [13]. As a result of their analysis, they observed that the NeQuick 2 model over-exaggerated TEC values at low latitude stations in the equatorial anomaly region. They also observed that for the region between the northern peak and the valley of the equatorial anomaly, IRI Plas performance was generally better than NeQuick 2 at maximum ionization times. Leong et al. evaluated the performance of IRI-2007, IRI-2012 and NeQuick 2 in the prediction of the ionospheric TEC in Banting [14].

In the studies about the performances of estimating the ionospheric parameters of the NeQuick 2 model, the emphasis is on the necessity of developing this model. In this study, the performances of NeQuick 2 model predicting VTEC values during severe geomagnetic storm process were investigated with various statistical methods. In next part 2 gives detailed information about the geomagnetic storm studied. Then it was expressed how the data used in the calculations obtained, and was discussed the Result and Discussions and Conclusions sections.

Features Of Severe Geomagnetic Storm On September 7-8, 2017

Figure 1 shows the variation with time of parameters used to define the storm. These parameters are the SYM-H, is use to expression "high resolution DST(Disturbance Strom Time), Proton Flux (PFLX> 10 MeV), Interplanetary Electric Field (IEF Ey), proton density (Np), proton speed (Vp) and the IMF Bz (z component of Interplanetary Magnetic Field). Coronal mass injection released from the sun led to a sudden storm commencement at 23:45 UT. SSC refers to the initial phase of the geomagnetic storm. At the same hour, the SYM-H amplified from 20 nT to 38 nT and the PFLX> 10 MeV value increased from 55.81 to 121.61 (1/cm^{2}s ster), while no other parameters were significantly altered. Then, the IMF Bz value rose to 15.31 nT in the north direction, Vp value to 601.5 km/h, Np value to 12.82 n/cc and IEF Ey value to -8.99 mV/m after approximately one hour from the SSC. After this time, the SYM-H, is value began to decrease, and on 08.09.2017 at 1:08 UT, the lowest value was -146 nT. This value indicates that the main phase of the severe geomagnetic storm has ended. The change of other parameters at the same time is as follows: IMF Bz value increased to about -30 nT, Vp value increased to 750-800 km/h, IEF increased about 20 mV / m and PFLX> 10 MeV 810 (1/cm^{2}s ster). In the recovery phase of this first storm, there was another deviation of -17.46 nT in the south direction in the Bz value at 11:55 UT on September 08 for about 4 hours. Then, SYM-H and Kp values reached -115 nT and 8.33 at 13:56 UT, respectively. Thus, this geomagnetic storm has two main phases.

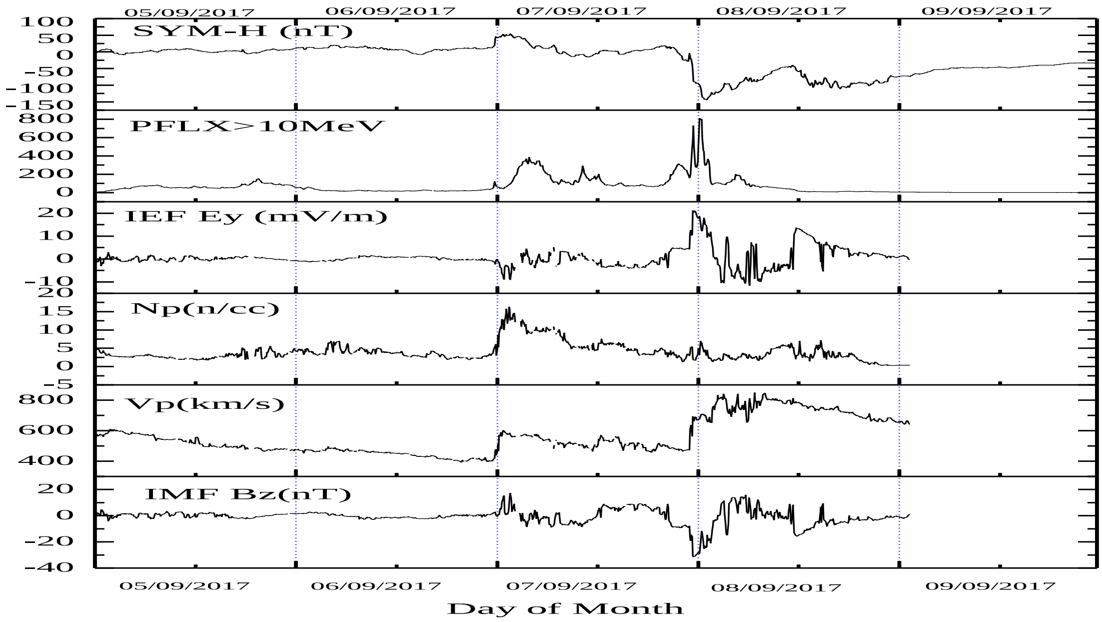

Figure 1. Changed in time of IMF *Bz*, *V*p, *N*p, IEF *Ey*, PFLX > 10 MeV and SYM-H indices used in this study on September 5-9, 2017 (Adapted from [15]).

VTEC Data

In the present study, VTEC measurements provided by GPS receivers in RINEX format were used. VTEC values for each station (total of five zones, ie 5 stations (NYAL (79.83 N, 11.87 E)), MEDI (44.51 N, 1.84 E), NKLG (0.35 N, 9.87 E), SUTM (32.28 S), 20.81 E) and SYOG (69.00 S, 39.58 E)) were obtained with both IONOLAB software and NeQuick 2 model. These stations and their coordinates are given in Table 1.

Table 1. Information on the stations used in this study

No	Station's name	Geographic latitude	Geographic longitude	Magnetic latitude	Magnetic longitude
1	NYAL	78.93	11.87	76.41	129.28
2	MEDI	44.51	11.64	44.72	94.41
3	NKLG	0.35	9.67	1.74	83.15
4	SUTM	-32.38	20.81	-32.65	88.06
5	SYOG	-69.00	39.58	-70.57	87.00

Raw data of GPS date are available in Receiver Independent Exchange Format (RINEX) with a resolution of 30 s. Raw data was processed via the software provided by the Ionospheric Research Laboratory (IONOLAB) group to obtain TEC data. IONOLAB-TEC provides accurate, reliable and robust GPS-VTEC estimation at high latitude, mid- latitude or equatorial GPS stations with the same reliability and accuracy for both quiet and active days (www.ionolab.org) [16-18]. The current version of IONOLAB-TEC, which can be used online or downloaded as * .exe from www.ionolab.org, can estimate the GPS-VTEC at the temporal resolution of any RINEX file. Therefore, if the data in the RINEX file is 1 s or 30 s, IONOLAB-TEC can produce the same temporal resolution. Since only the hourly VTEC values can be obtained by the web version of the NeQuick 2 model, the hourly values of the GPS-VTEC values for each day are used in the present study.

The NeQuick model includes a program that calculates electron density from any ground path to GNSS satellite altitudes of approximately 20200 km and is therefore convenient to compare with GNSS measurements. The latest version of the NeQuick model is the NeQuick 2 model, and in this study, the VTEC values were obtained using the internet interface of this model. The web address of the NeQuick 2 web model is https://t-ict4d.ictp.it/nequick2/nequick-2-web-model. When using this web address to obtain VTEC values, the Solar Radio Flux (source: NOAA-NGDC*)* option was selected from solar activity options. No changes were made to the other options. Thus, VTEC values for 05-09 September 2017 were calculated hourly, including 07/08 September 2017 geomagnetic storm, the most severe geomagnetic storm of the 24th Solar cycle [4, 5, 11].

RESULTS and DISCUSSIONS

The variation of the TEC values calculated by the NeQuick 2 model and measured by GPS for the NYAL station (78.93 N; 11.87 E) located in the upper latitude region of the northern hemisphere is shown in Figure 2. The NeQuick 2 model values exhibit a change that decreases as expected until sunrise, then the values reaches the maximum of noon and enters a decline again. However, there is a significant difference in the maximum and minimum time and the maximum and minimum TEC values obtained from the NeQuick 2 model and GPS. It was also observed that the NeQuick 2 model was not able to determine the second maximum movement of approximately 15:00 UT to 16:00 UT followed by a reduction of the TEC values following the first maximum at noon. The correlation coefficient between NeQ-TEC and GPS-TEC obtained on 08/09/2017, which includes the main phase of the storm, is r = 0.44, which is a very low value. The correlation coefficient is not high on other days. These values are 0.65, 0.72, 0.73 and 0.62 for the days (05, 06, 07 and 09), respectively. These investigations indicate that the NeQuick 2 model still needs to be developed for the northern hemisphere high latitudes, especially for the station under investigation and in geomagnetically stormy situations.

The variation of the TEC values calculated by the NeQuick 2model and measured by GPS for the MEDI (44.51 N; 11.64 E) station in the mid-latitude region of the northern hemisphere is shown in Figure 3. NeQ-TEC and GPS-TEC values reached about same minimum value at approximately the same time on all days. However, the situation is very different at noon, when TEC values are maximum. The values of the NeQ-TEC at noon are quite overestimated on all days, except on the day of the storm. Although there is a difference in amplitude at their maximum, the daily correlation values obtained are high. These values are 0.80, 0.90, 0.89, 0.88 and 0.85 in all days, respectively. However, it can be said that the NeQuick 2 model has overestimated TEC values on all days, except for except the day when the storm begins, namely September 07, 2017.

Figure 4 shows the variation of NeQ-TEC and GPS-TEC values with time for the NKLG station (0.35 N; 9.67 E) on the equator. The NeQ-TEC values exhibit a behavior in the form of camel hump at noon only at this station. It is observed that NeQ-TEC and GPS-TEC values reach the minimum at the about same time and with the about same values on all days, except sunrise

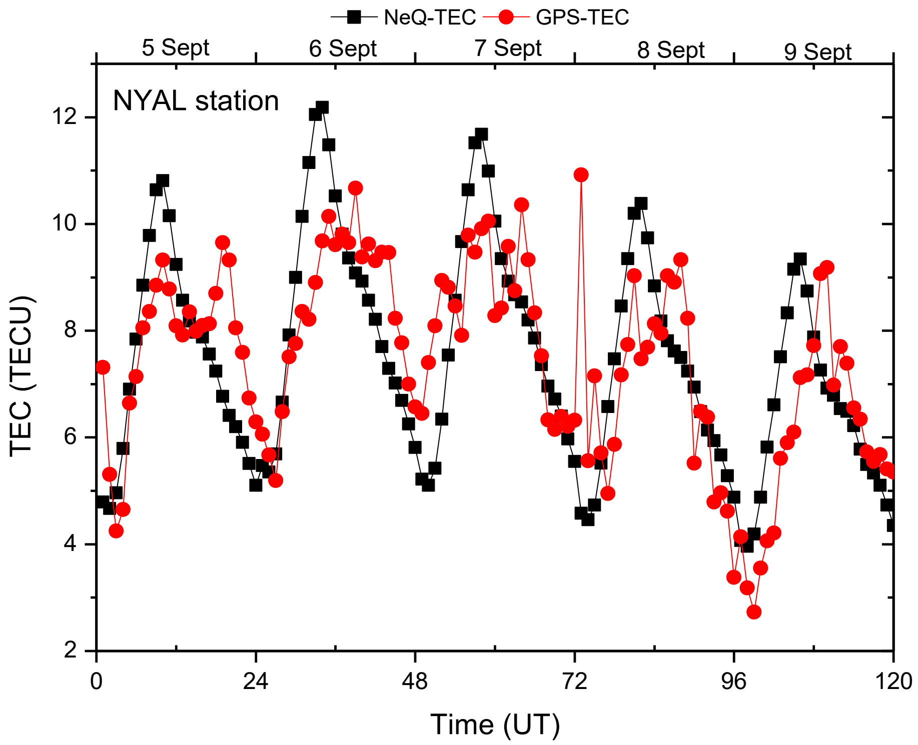

Figure 2. Variation of measured (GPS-TEC) and calculated (NeQ-TEC) TEC values at NYAL station over time.

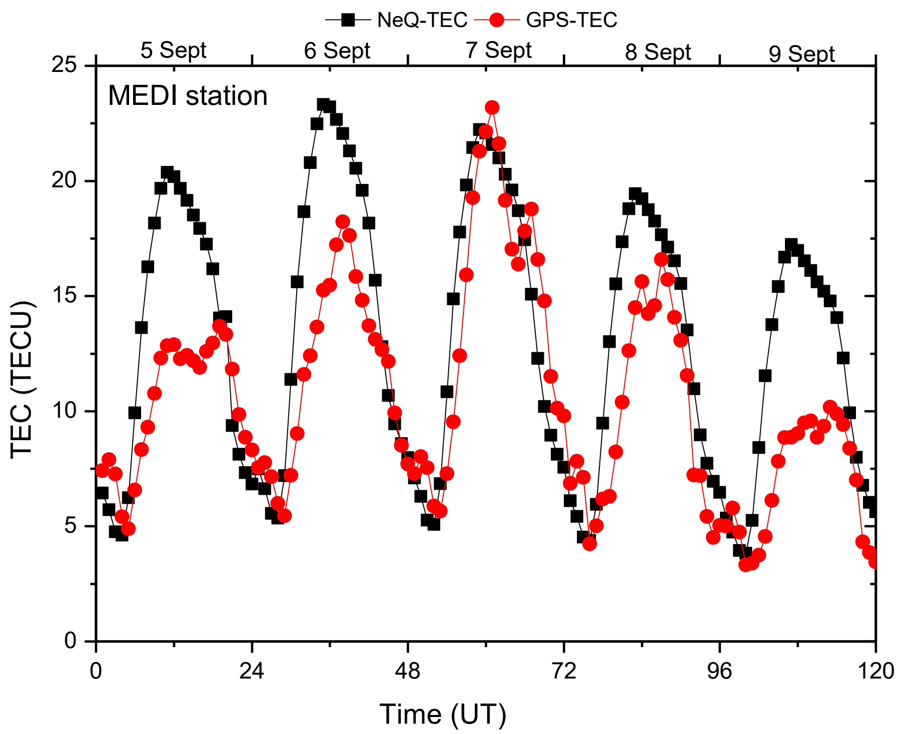

Figure 3. Variation of measured (GPS-TEC) and calculated (NeQ-TEC) TEC values at MEDI station over time.

on September 6. Excluding September 08, it said to be greater NeQ-TEC values than the GPS-TEC ones on other days. However, both TEC changes are very similar. This is also seen with high correlation coefficients. These coefficients between GPS-TEC and NeQ-TEC are 0.96, 0.92, 0.87, 0.90 and 0.94 on September 05-09, respectively.

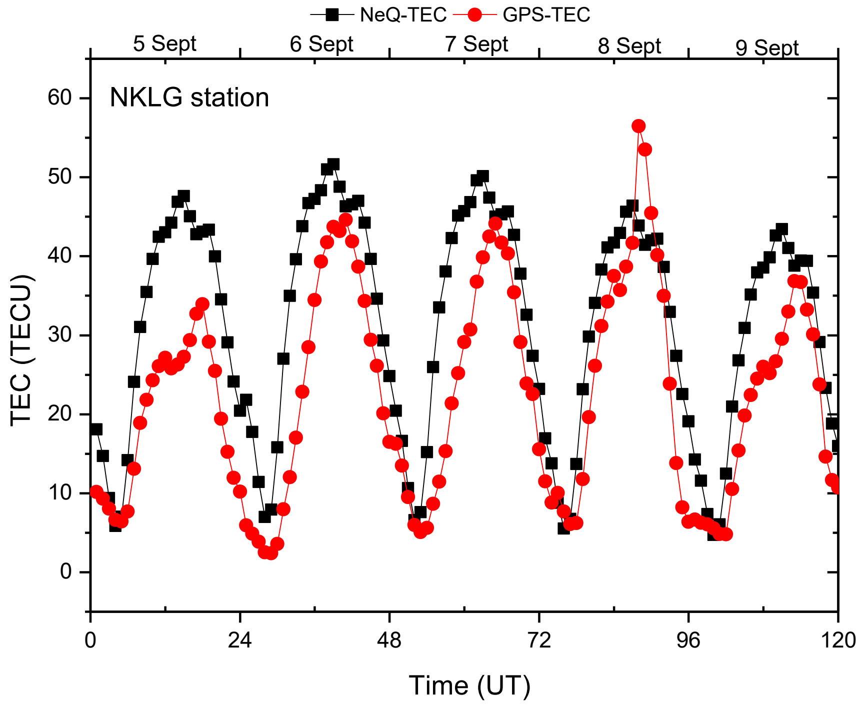

Figure 4. Variation of measured (GPS-TEC) and calculated (NeQ-TEC) values at NKLG station over time.

The variation of TEC values calculated by the NeQuick 2 model and measured by GPS for the SUTM station in the southern latitude region of the southern hemisphere is shown in Figure 5. The variation of NeQ-TEC and GPS-TEC values over time is very similar. The time periods when the TEC values are minimum are very close to each other. Similar situation is not the case on other days, except the main phase of the September 08 storm. The maximum value of NeQ-TEC is greater than the maximum value of GPS-TEC on other days. The correlation coefficient between NeQ-TEC and GPS-TEC is quite high. These coefficients are 0.94, 0.89, 0.91, 0.95 and 0.98 for September 05, 06, 07, 08 and 09 respectively. The coefficients indicate that the NeQuick model is highly compatible with GPS-TEC, except at noon maxima, especially in the mid-latitude region of the southern hemisphere.

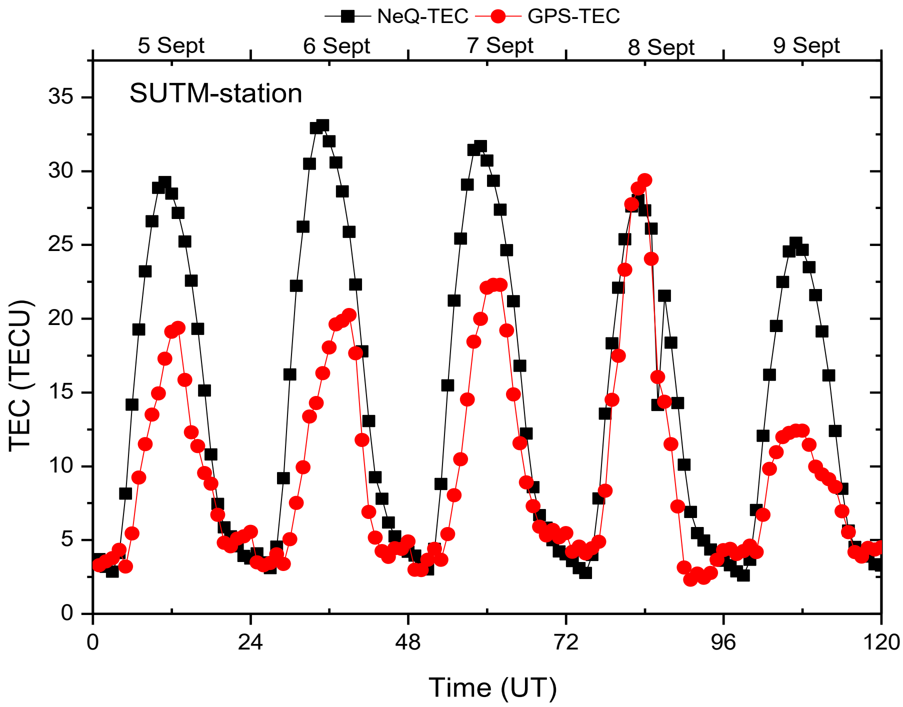

Figure 5. Variation of measured (GPS-TEC) and calculated (NeQ-TEC) values at SUTM station over time.

Figure 6 shows the variation of NeQ-TEC and GPS-TEC values over time for the SYOG station at high latitudes in the southern hemisphere. NeQ-TEC values show a normal daily distribution. However, GPS-TEC values show quite different distributions than normal distribution during the day, especially during sunrise hours. It is seen that the NeQ-TEC and GPS-TEC values are quite different, especially when they take the daily maximum and minimum values of TEC. It was observed that TEC changes at sunrise could not be determined adequately in the upper latitudes of southern hemisphere for this time period. However, it can be said that NeQ-TEC and GPS-TEC value changes outside this time period are similar. The correlation coefficients between NeQ-TEC and GPS-TEC values for the studied days were 0.84, 0.95, 0.84, 0.83 and 0.89, respectively.

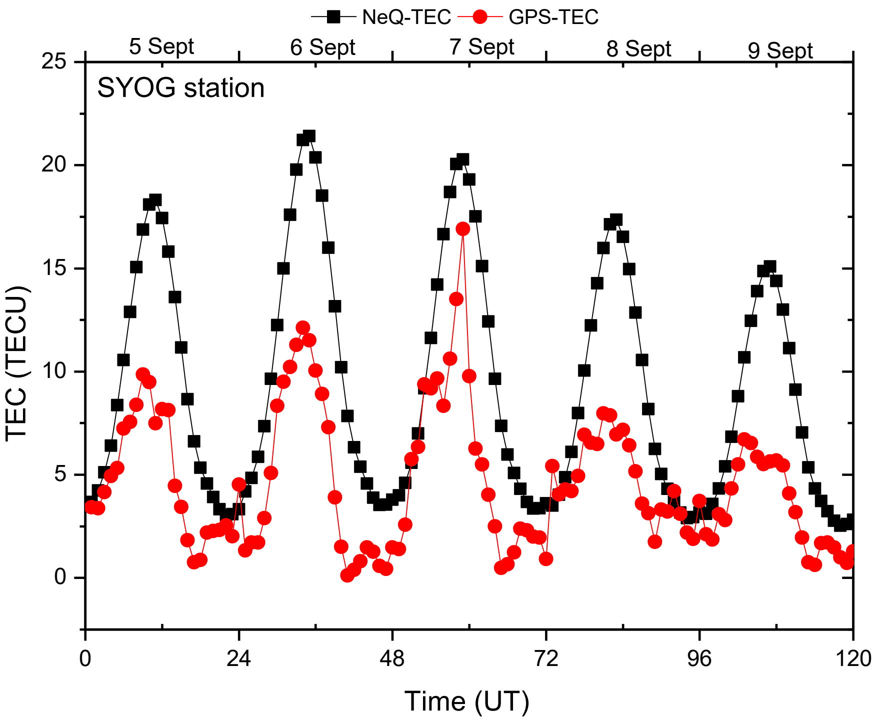

Figure 6. Variation of measured (GPS-TEC) and calculated (NeQ-TEC) TEC values at SYOG station over time.

Table 2. The values of RMSE, R, Maximum (Max) and Minimum (Min) deviation during this geomagnetic storm.

Station	5 sept				6 sept				7 sept				8 sept				9 sept			
	R	RMS	Max	Min	R	RMS	Max	Min	R	RMS	Max	Min	R	RMS	Max	Min	R	RMS	Max	Min
NYAL	0,65	1,43	2,91	-1,79	0,72	1,44	2,17	-3,15	0,73	1,37	2,67	-2,05	0,44	1,89	6,34	-2,91	0,62	1,48	2,26	-3,05
MEDI	0,80	4,76	2,51	-7,53	0,90	4,67	1,60	-8,82	0,89	2,78	4,59	-5,37	0,88	3,71	2,60	-7,31	0,85	5,10	1,04	-8,37
NKLG	0,96	12,98	0,77	-20,60	0,92	12,57	-1,72	-22,94	0,87	11,94	-0,59	-22,74	0,90	8,22	12,61	-14,3	0,94	9,12	0,85	-15,9
SUTM	0,94	7,35	1,81	-13,95	0,89	9,40	0,70	-18,64	0,91	7,38	1,43	-14,95	0,95	3,70	2,06	-7,19	0,98	7,00	1,67	-12,73
SYOG	0,84	5,55	1,21	-10,82	0,95	6,52	-2,31	-10,32	0,84	5,65	0,20	-11,25	0,83	5,39	1,92	-10,4	0,89	5,07	-0,99	-9,45

For comparison and more quantitative interpretation of the results obtained, the results of some statistical procedures including the maximum and minimum deviation and root mean square error (RMSE) test according to the differences between GPS-TEC and NeQuick 2 model were presented in Table 2. As seen on the table, the NeQuick 2 model overestimated the TEC values at all stations and all days, except for 8 Sept. in NYAL station. The reason is that the min values are generally larger than the max values as can be seen from the table. Here, it can be said that when the deviation (GPS_{TEC}-$MODEL_{TEC}$) is positive, the model underestimates the TEC values, and when the deviation is negative, the model overestimates the TEC values. The greatest deviation between the difference values was observed at the NKLG station for all days.

However, in the same station, the excessive exaggeration of the NeQuick 2 model decreased on storm day (8 Sept.) compared to other days. The high deviation of this station in the equatorial region may be related to the anomalies occurring in this region which are still not fully understood. The station where the NeQuick 2 model underestimates the VTEC values is again the NKLG station. The maximum deviation was achieved at this station with 12.61 TECU on the day of the storm. On the other hand, the maximum deviation values at the same station are very small. Changes in both maximum and minimum deviation on the day of the storm lead us to the conclusion that the NeQuick 2 can detect ionospheric changes during the storm. When a change similar to NKLG for the other station was examined, it was observed that there was a similar behavior only at the STUM station. So, on 8 Sept. the Max values at the STUM station increase while min. values decrease. Moreover, the prediction performance of the model decreases as min value moves away from zero. It can be said that the model makes the best predictions for all days at the NYAL station. It is seen that NeQuick 2 model made the worst estimations again at the NKLG station. However, at the NKLG and STUM stations, the similar changes observed in the max and min differences were also observed in the RMSE values. It is seen that the RMSE values are decreased in both NKLG and STUM stations on storm day compared to other days, that is, the predictive performance of the model has increased on the storm day. The greatest deviation between the difference values was observed at the NKLG station for all days. However, in the same station, the overestimation of the NeQuick 2 model decreased on storm day (8 Sept.) compared to other days. The high deviation at this station located in the equatorial region may be related to the equatorial anomalies occurring in this region, which are still not fully understood. The station where the NeQuick 2 model underestimates the TEC values is again the NKLG station. The maximum deviation was achieved at this station with 12.61 TECU on the day of the storm. On the other hand, the maximum deviation values at the same station are very small. Moreover, since the predictive performance of the model decreases as this value moves away from zero, according to the RMSE values, it can be said that the model makes the best predictions on all days of NYAL station. It is seen that this model made the worst estimates again at the NKLG station. However, at the NKLG and STUM stations, the changes observed in the max and min differences were also observed in the RMSE values. It is seen that the RMSE values are decreased in both NKLG and STUM stations on storm day compared to other days, that is, the predictive performance of the model has increased.

CONCLUSIONS

In this study, TEC values calculated by NeQuick model and measured by GPS for 5 different stations and 5 different latitude regions were studied for days of the pre- and post-severe storm time of 07-08 / 09/2017. The results obtained are listed below.

• The Performance of the NeQuick 2 model in the northern hemisphere is low. The reason for this may be that it is not found in the NeQ-TEC model the "camel hump" behavior at noon in the northern hemisphere TEC values.
• The performance of the NeQuick 2 model decreases as you move from the equator to the poles.
• The NeQuick model only models the "camel hump" behavior that occurs at noon in the equator. However, this behavior should be in the northern hemisphere.
• It can be said that the NeQuick 2 model is very successful in calculating the minimum value of TEC during the day except for the southern hemisphere upper latitudes.
• The NeQuick model generally exaggerated its maximum TEC values at noon. This exaggeration is approximately the effect of the main phase of the geomagnetic storm for the SUTM station.

In addition, the NeQuick 2 model is a very important model for space weather where few measurements can be made. The ways to reduce the difference between NeQ-TEC and GPS-TEC values can be found by monitoring past geomagnetic storm processes with the help of machine learning and artificial intelligence programs.

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