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Research article

Applicability of NeQuick G ionospheric model for single-frequency GNSS users over India

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Abstract: The major source of error in the positioning of GNSS is from the region of Ionosphere. The single-frequency GNSS receiver cannot eliminate the ionospheric error due to dispersive medium and frequency-dependent. The low-cost GNSS receivers are highly dependent on single-frequency approaches of Ionosphere region popularly known as Klobuchar, NeQuick G, and BDS2 methods to estimate the data of position, velocity and time. The regional satellite navigation system of India, known as Navigation with Indian Constellation (NavIC) adopted ionospheric models based on single-frequency namely, Klobuchar and grid-based correction models. The Klobuchar model's accuracy is less for predicting ionospheric delays in low latitude regions like India under Equatorial Ionization Anomaly (EIA) conditions. In this paper, the NeQuick G model's applicability for NavIC users over the Indian region is investigated. NeQuick G model's performance is validated with dense GPS TEC network data of 26 stations spread across India and IRI-2016 model, during 2014, 2015 and 2016. The predicted TEC results indicate that EIA structures are well captured by NeQuick G and IRI-2016 models. The results indicate that both NeQuick G and IRI-2016 models well predict season asymmetry and decrease of TEC intensity due to descending phase solar cycle activity. It is found that NeQuick G is one of the contenders of single frequency ionospheric models for GNSS/NavIC users in India.

Keywords: GNSS; NavIC; Equatorial Ionization Anomaly (EIA); NeQuick G; IRI 2016

1. Introduction

The variability of equatorial region as well as lower latitude region of Ionosphere is because of extensive electrodynamics related to EIA, plasma fountain, Equatorial Electrojet (EEJ), temperature anomaly, equatorial wind etc. EEJ is the improved day-time electric current eastwards in the E-layer, due to strong vertical polarized electric field produced in the latitudinal belt of ±3 degrees around dip equator. Various ionospheric models have been investigated to demonstrate the irregularities in the regions of inadequate measurements besides reducing the ionospheric signal delay for trans-ionospheric radio wave propagation [1]. The electric field produced at the dip equator is being mapped on to the region of F-layer along E × B drift, lifting plasma to high altitudes [2]. Ionospheric region cause significant loss of data in the stream of communication and navigational applications. Estimating the accurate value of total electron content (TEC) especially in equatorial and low-latitude region seems to be a difficult task due to substantial spatial and temporal gradients during the times of EIA occurrence [3]. The value of TEC is given by 1 TECU = 10^{16} electrons/m². GNSS gives an opportunity to monitor Ionosphere through its signals. GNSS signals measure TEC using GNSS carrier and code phase observations. The total measure of electrons available alongside the path from the transmitter to the receiver is termed as TEC. India has developed a satellite based GNSS augmentation system named by GPS Aided Geo Augmented Navigation (GAGAN) and autonomous regional satellite-based navigational system known as Navigation with Indian Constellation (NavIC)/IRNSS. NavIC comprises of 3 GEO and 4 GSO satellites. NavIC satellites transmit signals in both L5 (1164.45–1188.45 MHz) and S-bands (2483.5–2500 MHz) by a carrier frequency of F1 (1176.45MHz) and F2 (2492.08MHz) respectively [4]. IRI-International Reference Ionosphere sponsored by COSPAR (Committee on Space Research), an empirical standard model of ionospheric region, synthesize with many models based upon the available data from all sources of COSPAR. In recent times, IRI has been broadened to plasmasphere termed as IRI-Plas 2017 model, for a better understanding of the study of variations in plasmasphere region of Ionospheric layer at an altitude of the GPS satellite around 20,200 km, as well as characterizing the topside electron density profiles considering the TEC data as key parameter. IRI-Plas 2017 model was demonstrated as a candidate model for the broadening of plasmasphere region with regard to IRI model [5]. Similar studies were carried out in view of the presentation of IRI-Plas model by considering GPS-TEC [6–10]. Klobuchar proposed a global ionospheric delay model called Ionospheric broadcasting model (IBM) to benefit the single-frequency users of GPS. The model performs ionospheric corrections in real-time, by using just eight coefficients in the navigation message of global positioning system. The regular improvement models with respect to ionospheric delay have limited capability to deal with both normal and calm-space weather conditions. However, adverse space weather disturbances remain unsolved in most of the satellite navigation applications [11]. Approximately, the model reduces the effects in Ionosphere region up to 50% by using these coefficients [12]. NeQuick-G model provides electron density distribution with a height up to F2 peak based on Epstein layer (DGR, 1990) [13]. The improved NeQuick model as proposed by Radicella and Zhang (1995) would give electron density profiles on both top side and bottom side of ionospheric region including the total electron content (TEC) [14,15]. NeQuick G is an official single frequency ionospheric model for Galileo, the satellite navigation system of Europe. NeQuick G model being simple requires only three broadcast coefficients to estimate ionospheric correction for estimating position estimation using GNSS receivers. The applicability of NeQuick G model for the single-frequency GNSS users across India is investigated in this paper. The 26 ground-based GPS TEC data recorded over India is taken for the analysis. NeQuick G model performance is compared with IRI 2016 model and multi-GPS TEC observations. The analysis of the work carried out will be useful to identify a suitable global ionospheric model for single-frequency users of GNSS.

2. Data Processing

The dense GAGAN TEC stations network data (26 stations) across India is considered for validation of NeQuick G model. The GPS TEC data is provided by Space Applications Centre, ISRO, India for the years 2014–2016. The GPS TEC information is obtained from Novatel GSV400B dual-frequency GPS receivers. The GPS Seconds of the week, GPS week number, GPS satellite PRN number, station index number, Elevation and Azimuth angles of satellite and TEC are extracted from the data sets. A threshold of 30° on elevation angles is fixed as a satellite mask angle to reduce the multipath effect on GNSS signals. The observations of Slant TEC (STEC) are transformed into vertical TEC (VTEC) by using the mapping function [16]. The VTEC corresponding ionospheric pierce point (IPP) locations in terms of latitudes and longitudes are calculated. Krishna et al. (2020) developed Adjusted SHF (Spherical Harmonics Function) model for order 4 to generate Indian regional ionospheric TEC maps [17]. The 25 ASHF coefficients are generated every 5 minutes to represent the state of the ionosphere. The 25 ASHF coefficients are utilized to derive the ionospheric TEC values at each ionospheric grid point of with a spatial grid resolution of 5° × 2.5°. Most of the GNSS applications are exposed to positioning performance degradation during the times of positive phase and negative phase of geomagnetic storm conditions [18]. The GPS TEC observations are considered for the three years choosing quiet and disturbed days as shown in Table 1. Data are selected for three years 2014, 2015 and 2016 of distinct type of solar activity high, medium and low respectively. Also, data comprising of seasonal variations are also added from two equinoctial months March and September, summer solstice month June and winter solstice month December. The most quiet and disturbed days are selected in these months.

2.1. IRI 2016 model

International Reference Ionosphere (IRI-2016) model is a conventional model proposed under COSPAR collaboration and International Union of Radio Science (URSI). IRI-2016 is an empirical model of Ionosphere upto 2000 Km in height. It provides a three-dimensional distribution of parameters in Ionosphere region namely, electron density, electron temperature, ion temperature, and ion composition. The IRI model's primary data sources are from incoherent scatter radars, network of ionosondes, and other in-situ measurements. Upon several model editions, the IRI-2016 is the latest version and is used for our study. The TEC data for the Indian region from the IRI-2016 model is obtained through request-on-run from Community Coordinated Modeling Centre (CCMC). The data can be downloaded from https://ccmc.gsfc.nasa.gov/models/modelinfo.php?model=IRI.

2.2. NeQuick G model

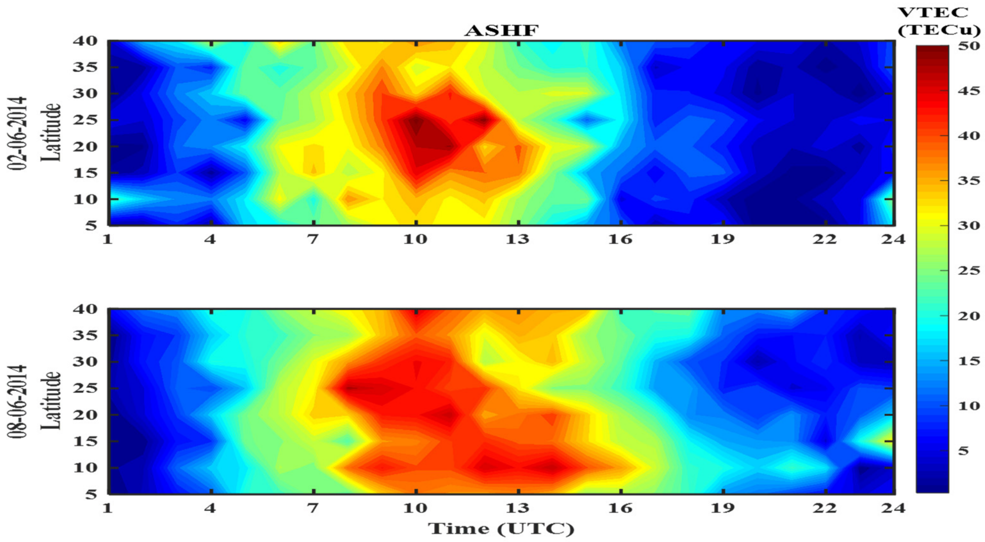
NeQuick-G predicts the monthly mean electron density from the analytical profiles depending on the solar activity input parameters such as Sun Spot Number (SSN), month, both geographic latitude and longitude, height and universal time (UT) [19]. And hence, quiet and disturbed day's data are selected for three different years 2014, 2015 and 2016 with high, medium and low solar activity respectively to analyse the performance of the model. NeQuick G model has been adapted for single-frequency ionospheric corrections of European navigation system in real-time to gain real-time predictions depending upon the input parameter, Effective Ionization Level, Az. Az is computed using 3 broad cast coefficients in the navigation message. NeQuick G is chosen for implementation in Galileo user equipment consistent with the three broadcasting coefficients. As described by NeQuick model, the global Ionosphere's electron density is specified by two types of inputs: time (month and universal time) and the three broadcasting coefficients (a01, a02, a03). The three NeQuick G broadcast coefficients for the considered days are loaded from the link: ftp://ftp.gipp.org.cn/product/brdion/. The program based on python is taken from https://github.com/tpl2go/NeQuickG for implementing the NeQuick G ionospheric correction model. The NeQuick G TEC maps are generated for selected day across India, for geographic longitude and geographic latitude of 65° to 100° and 5° to 40° respectively. The application of NeQuick G model over India, for single frequency GNSS users is validated with GPS TEC and IRI 2016 models.

Table 1. Details of Selected days of months' during March & September Equinox and June & December Solstice in the period 2014–2016.

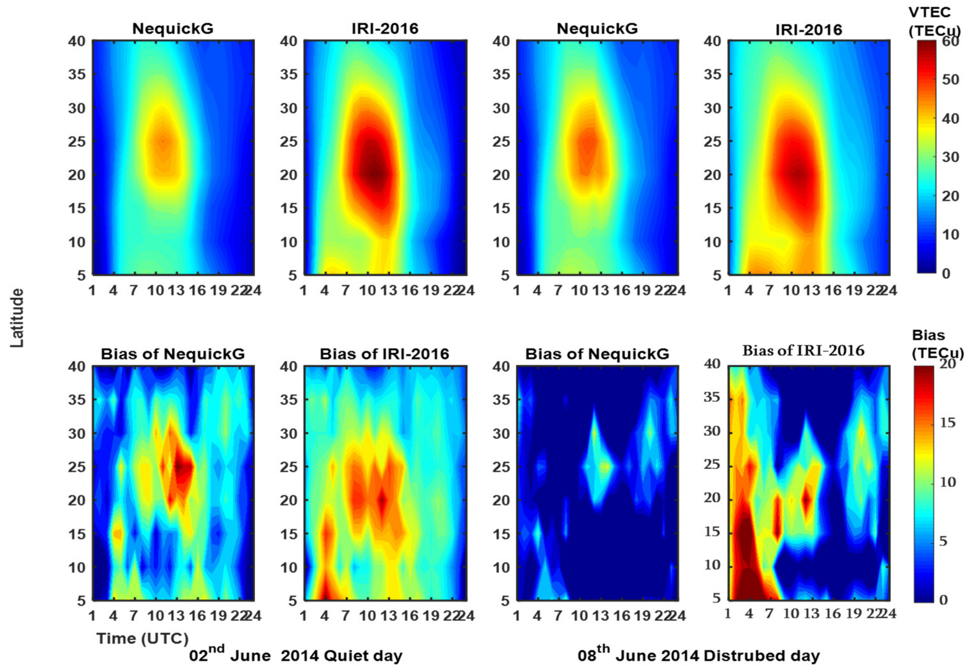
S.No	Date	Season	Quiet/Disturbed	Kp Index
1	10-03-2014	Summer Equinox	Quiet day	2
2	13-03-2014	Summer Equinox	Disturbed day	4
3	14-09-2014	Autumn Equinox	Quiet day	1−
4	12-09-2014	Autumn Equinox	Disturbed day	6+
5	02-06-2014	Summer	Quiet day	2+
6	08-06-2014	Summer	Disturbed day	6+
7	14-12-2014	Winter	Quiet day	3+
8	07-12-2014	Winter	Disturbed day	5−
9	05-03-2015	Summer Equinox	Quiet day	2+
10	17-03-2015	Summer Equinox	Disturbed day	8−
11	27-09-2015	Autumn Equinox	Quiet day	1+
12	09-09-2015	Autumn Equinox	Disturbed day	6
13	05-06-2015	Summer	Quiet day	0+
14	23-06-2015	Summer	Disturbed day	8−
15	03-12-2015	Winter	Quiet day	1+
16	20-12-2015	Winter	Disturbed day	7−
17	05-03-2016	Summer Equinox	Quiet day	2
18	07-03-2016	Summer Equinox	Disturbed day	5−
19	12-09-2016	Autumn Equinox	Quiet day	2
20	03-09-2016	Autumn Equinox	Disturbed day	6−
21	07-06-2016	Summer	Quiet day	3
22	05-06-2016	Summer	Disturbed day	5+
23	05-12-2016	Winter	Quiet day	2+
24	09-12-2016	Winter	Disturbed day	5−

3. Results and discussions

To analyze the performance of NeQuick G ionospheric model over Indian region, data observations from 26 GPS TEC stations are considered for a total of 12 quiet and 12 disturbed days during the three years 2014, 2015 and 2016 of different solar activity. The corresponding TEC values are computed using ASHF model for the order 4, driven by 25 coefficients. TEC data for the lower latitude India region is considered from IRI-2016 model for validation of NeQuick G model.



a



b

Figure 1. a: EIA peak recognition using ASHF, on geomagnetic quiet (02nd June 2014) and geomagnetic disturbed (08th June 2014) days. b: EIA peak recognition using NeQuick G, IRI-2016 and bias of IRI-2016, NeQuick G for geomagnetic quiet (02nd June 2014) and geomagnetic disturbed (08th June 2014) days.

3.1. Quiet day condition

Figure 1a depicts the ionospheric TEC variability of GPS TEC using ASHF on geomagnetic quiet (02^{nd} June 2014) and geomagnetic disturbed (08^{th} June 2014) days. Figure 1b shows the ionospheric TEC variability using NeQuick G and IRI-2016 models and also biases of IRI-2016 and NeQuick G on geomagnetic quiet (02^{nd} June 2014) and geomagnetic disturbed (08^{th} June 2014) days. The x axis denotes time in UT and y-axis denotes the latitude. It can be observed from Figure 1a that movement and development of full EIA structure are noticed between the latitudes range between 15 to 28 degrees. The maximum EIA peak TEC (50 TECU) was noticed at 10 UT at 25 degrees latitudinal band for quiet day conditions. NeQuick G and IRI 2016 model predicts EIA structures in the same range of GPS TEC observations. The maximum TEC of EIA crest values are noticed at 10 UTC. The difference between model and observed TEC values are computed and termed as bias values, as shown in Figure 1b. The bias values for NeQuick G model are as low as compared to IRI 2016 model. The quiet day results indicate that NeQuick G model performed better than IRI 2016 model.

3.2. Disturbed day condition

Figure 1b shows GPS TEC variations for the disturbed day conditions. The downward shift of EIA has observed during the hours 10 to 16 UT. NeQuick G model predicted the EIA crest at 25 degrees latitude at 12 UT indicated the depleted EIA structures. IRI-2016 model also captures the smooth EIA structures as compared to NeQuick G and GPS TEC data. It is evident that residual error distribution is low as compared to IRI-2016 model.

A comparative analysis of the ionospheric models is carried out for 12 quiet days spreading in three years in each season. Figure 2 illustrates the EIA variations of ASHF, IRI-2016, NeQuick G, and bias of IRI-2016 and NeQuick G, of months March, June, September and December during 2014, 2015 and 2016 on geomagnetic quiet day. The x-axis indicates four months of three years and y-axis represents time in UT. As shown in Figure 2, during the period 2014–2016, the EIA phenomenon is observed at low latitude range of 10 to 20 degrees at the time of 05:00 UT to 15:00 UT, for ASHF and IRI-2016 models. It is also observed that during the same time, EIA structures captured are better for NeQuick G model compared to ASHF and IRI-2016 models. GPS TEC and NeQuick G and IRI-2016 models are shown decay of TEC intensity as the number of years increase from solar maximum to descending phase year (2016). For the year 2014, the maximum EIA structures are observed for the summer equinox day (1) and autumn equinox day (3) for both GPS TEC and NeQuick G models. However, IRI-2016 model overvalued the TEC values. Further, season asymmetry is clearly predicted by NeQuick G model when compared to the IRI-2016 model. The lower bias values for NeQuick G model are indicating that following GPS TEC observations over the Indian region. It is clearly seen that TEC trends for winter season day are low as compared to other seasons. However, the IRI-2016 model overestimated TEC values during winter seasonal days. For the year 2015, the NeQuick G model has underestimated TEC values, whereas IRI model overestimated the TEC values compared to GPS TEC data. Both IRI-2016 and NeQuick G models predicted seasonal asymmetry feature well. The EIA densities are low for winter season day as compared to other seasons. IRI 2016 overestimated, and NeQuick G model underestimated with GPS TEC data for summer and summer equinox days. The bias value of IRI-2016 model is more extensive than NeQuick G model (Figure 2). For the year 2016, the NeQuick G model predicts EIA TEC characteristics where the IRI 2016 model is overestimated.

The full EIA is developed for both equinox days. The TEC intensities of EIA are lower for winter season day than compared to summer day. The bias results indicate that the NeQuick G model performed better than IRI 2016 model over Indian region for quiet conditions.

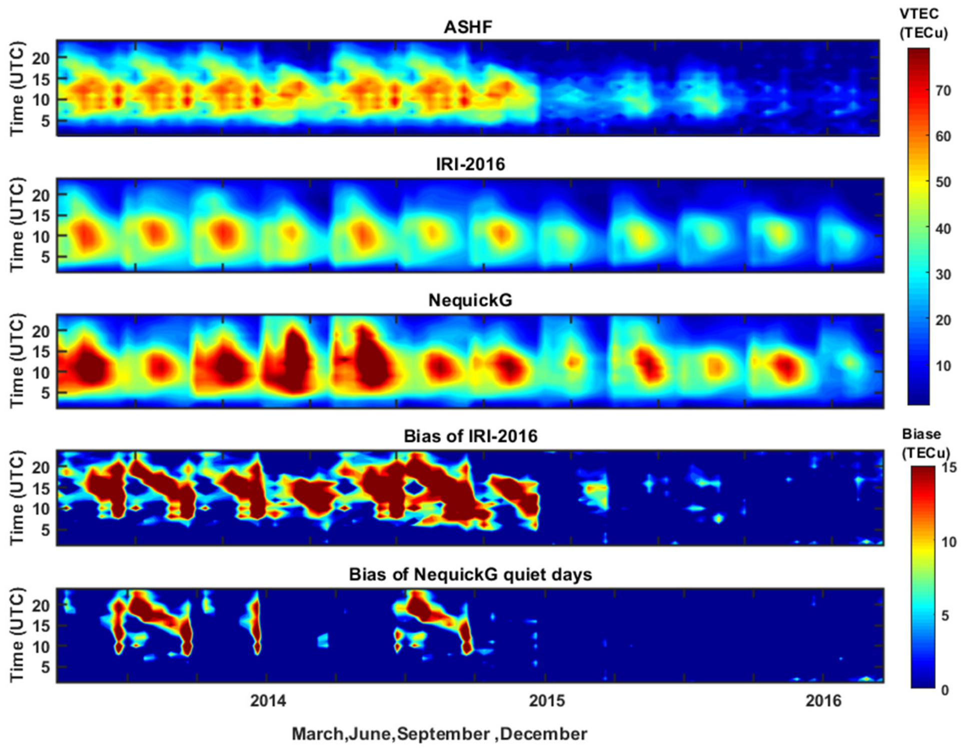


Figure 2. EIA peak recognition using ASHF, IRI-2016, NeQuick G, and bias of IRI-2016, NeQuick G on geomagnetic quiet days from 2014 to 2016.

Figure 3 illustrates the EIA variations of ASHF, IRI-2016, NeQuick G, and bias of IRI-2016 and NeQuick G, of the months March, June, September and December during the years 2014, 2015 and 2016 on geomagnetic disturbed day. The x-axis indicates four months of three years and y-axis represents time in UT. The Figure 3 panel shows observed GPS TEC variations for disturbed conditions. As shown in Figure 3, during the period 2014–2016, the EIA phenomenon is observed at low latitudes from 10 to 20 degrees at the time of 05:00 UT to 15:00 UT, for ASHF and IRI-2016 models and during the time of 05:00 UT to 20:00 UT for NeQuick G model during the month of March and gradually depletions have started for the months June, September and December. It is observed clearly that, the EIA structures are depleted due to geomagnetic disturbed conditions especially for ASHF, compared to IRI-2016 model and NeQuick G model. Also, Figure 3 depicts that NeQuick G model performs well even under adverse space weather conditions. It is noted that season asymmetries are observed for all three years (2014–2016). Also, TEC values of NeQuick G model follow the GPS TEC observations for the year 2014. The NeQuick G model is overestimated for the years 2015 and 2016. The IRI model predicted the EIA structures with overestimated TEC intensities for all the years. The bias results indicate the NeQuick G model performed better compared to IRI -2016 model under disturbed ionospheric conditions.

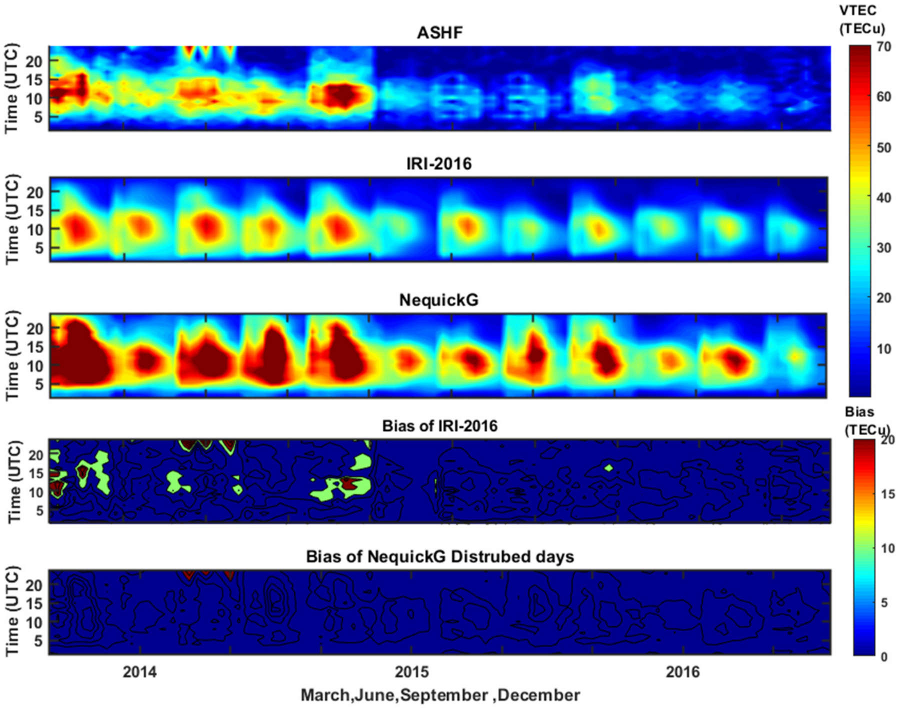


Figure 3. EIA peak recognition using ASHF, IRI-2016, NeQuick G and bias of IRI-2016, NeQuick G on geomagnetic disturbed days from 2014 to 2016.

4. Conclusions

This paper mainly concentrated on the validation of NeQuick G ionospheric model over the Indian region. Ionospheric TEC maps were generated for GPS TEC, IRI2016, and NeQuick G models for 12 quiet and 12 disturbed days spreading in three years (2014–2016). The TEC bias results indicate the better performance of NeQuick G over the IRI2016 model. NeQuick G model well models EIA structures full development for quiet day conditions and depleted EIA TEC structured for disturbed days. The NeQuick G model has slightly outperformed the IRI-2016 model compared to GPS TEC observations. Also, seasonal asymmetry features are well captured by both NeQuick G and IRI 2016 models. The results illustrate that the NeQuick G ionospheric model is one of the suitable candidates for selection of single frequency ionospheric model for GNSS/NavIC users. Both the validation and improvement of NeQuick G model under adverse space weather conditions over the Indian region will be carried out shortly.

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Conflicts of interest

The authors declare no conflict of interest.

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