Assessment and Validation of Three Ionospheric Models (IRI-2016, NeQuick2, and IGS-GIM) From 2002 to 2018

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Abstract It is important to confirm the accuracy and reliability of commonly used ionosphere models climatologically. In this contribution, International Global Navigation Satellite System Global Ionospheric Maps (IGSG) and two empirical models, that is, NeQuick2 and IRI-2016, are assessed in detail by applying different assessment methods, for example, Jason2/3 ionospheric data, difference of Slant Total Electron Content (dSTEC) data derived from Global Navigation Satellite System (GNSS) phase observation, and single-frequency precise point positioning. Compared with IGSG, the biases mainly range from −10 to 10 Total Electron Content Unit (TECU) for IRI-2016 and NeQuick2 models, respectively. Over the oceanic region, the mean biases for IRI-2016 and NeQuick2 models relative to Jason2/3 Vertical Total Electron Content (VTEC) are smaller than that of IGSG. The Root Mean Square (RMS) values are 4.8 and 6.0 TECU for IGSG and empirical models relative to Jason2-VTEC while the values are 5.4 and 6.0 TECU with relative to Jason3-VTEC. Compared with dSTEC values derived from the selected stations, the RMS values are about 1.8 and 2.6 TECU for IGSG and empirical models, respectively. In the positioning domain, the accuracy of single-frequency precise point positioning corrected by the three models can reach 1 m in three-dimensional direction. The positioning accuracy is 0.17 m corrected by IGSG and 0.50 m corrected by IRI-2016 and NeQuick2 in the horizontal direction.

1. Introduction

The ionospheric delay is one of the main errors for the Global Navigation Satellite System (GNSS), which can range from meters to tens of meters and be corrected by dual-frequency or multifrequency combination due to the dispersive nature of the ionosphere (Hernández-Pajares et al., 1999; Hernández-Pajares et al., 2011; Klobuchar, 1991). However, the combination method is not available for GNSS single-frequency users. Hence, various ionospheric models are employed to eliminate ionospheric delay for single-frequency users, which can be classified into three kinds. The first is physical models, which is solved by a set of energy and momentum equations for the plasma, including the Time Dependent Ionospheric Model (TDIM) (Schunk et al., 1986) and Coupled Thermosphere–Ionosphere Model (CTIM) (Fuller-Rowell et al., 1987). The second is parametric models. Models of this kind, such as the Parameterized Ionospheric Model (PIM) (Daniell, 1991), can simplify the physical model by parameterizing solar-terrestrial index and geographic location. The last is empirical models, which are constructed based on historical observation data, including International Reference Ionosphere (IRI) (Bilitza & Rawer, 1992), Bent (Bent et al., 1975), and NeQuick (Hochegger et al., 2000).

The empirical models can provide three-dimensional (3D) ionospheric electron profiles as well as Total Electron Content (TEC) along the ray path of GNSS electromagnetic wave. However, they only describe the long-term averaged condition of the ionosphere since they are formulated based on the monthly median parameters (Feltens et al., 2011). On the other hand, the grid ionospheric vertical delays broadcasted by the Satellite-Based Augmentation System (SBAS) can provide ionospheric correction with higher accuracy (Wu et al., 2014). The broadcast ionospheric models, which have few parameters and are easy to use, are widely

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used for ionospheric delay correction for single-frequency GNSS users, such as the Klobuchar model (Klobuchar, 1987) and its refined models (Yuan et al., 2008), the NeQuick model (Angrisano et al., 2013; Brunini et al., 2011; Nava et al., 2008), the NTCM model (Hoque & Jakowski, 2015) and its modification MNTCM-BC (Zhang et al., 2017), or the BDS broadcast model and its improvements (Wang et al., 2018; Yuan et al., 2019). Recently, with the development of communication and Internet technology, real-time GNSS observation data can be easily obtained to estimate real-time Global Ionosphere Maps (GIMs). Currently, its accuracy is slightly worse than that of 1 day predicted GIM and International GNSS Service (IGS) final GIM (IGSG) (Ren et al., 2019). The widely used two-dimensional ionospheric models have the following limitations. First, it ignores the vertical structure of the ionosphere based on the single-layer assumption. Second, the height of the single layer is typically fixed as a constant between 350 and 450 km. Third, the ionospheric mapping function will affect its accuracy significantly. Unlike two-dimensional ionospheric models, 3D ionospheric models, for example, IRI and NeQuick models, can provide the electron density between two given altitudes in space and the ionospheric information on the signal propagation path by means of numerical integration. Some previous assessment and comparison results of IRI and NeQuick models can be found in studies presented by Swamy et al. (2013), Andreeva et al. (2011), and Themens et al. (2014). Olwendo et al. (2012) evaluated the performance of IRI-2007 model from 2009 to 2010 in low-latitude zone over the Kenyan region. Akala et al. (2015) assessed the accuracy of IRI-2012 model for 4 years over Addis Ababa. These two studies mainly focused on the performance of IRI model over a small region. Radicella et al. (2008) assessed the accuracy of NeQuick2 and Klobuchar model using global IGS stations for the year 2000. Mengistu et al. (2018) examined the performance of NeQuick2 and IRI models in describing the monthly and seasonal mean variation over the low latitude East African region during different solar activity periods. Besides, GPS–TEC, GIM, and altimeter Vertical TEC (VTEC) are used to validate their performance (Rabiu et al., 2014; Wang et al., 2016). However, their assessment period is not long enough.

With the increasing number of Low Earth orbit (LEO) satellites in the near future, 3D ionosphere model will play an essential role in GNSS global ionospheric modeling augmented by LEO satellites (Ren et al., 2020). The increasing demand for ionospheric and space geodetic applications makes it of particular importance to assess the performance of the 3D ionospheric models from different aspects for the long-term comprehensively. On the other hand, IRI-2016 and NeQuick2 are the latest versions for corresponding models, and few studies have presented to show their performances for the long-term and IGSG. In this sense, this paper will fill this gap. A brief introduction of the empirical models is presented first. Afterward, the performance of each model is evaluated using different methods: (1) compare GIMs obtained from the empirical models with IGSG; (2) validate against altimeter VTEC data; (3) assess the models by the difference of Slant Total Electron Content (dSTEC) technique based on GNSS phase observations; (4) evaluate the positioning accuracy of single-frequency precise point positioning (SF-PPP) corrected by these models. Finally, summaries and conclusions are presented.

2. IRI-2016, NeQuick2, and IGS Final GIMs

IRI model is a standard empirical model sponsored by the Committee on Space Research (COSPAR) and International Union of Radio Science (URSI) and has been recognized as an international standard for the ionosphere since 1999 (Liu et al., 2019). It is the International Standardization Organization (ISO) standard for the ionosphere. Generally, the IRI model is generated by the worldwide network of ionosondes, the powerful incoherent scatter radars, topside sounders, and in situ instruments flown on many satellites and rockets. The model is updated as new data become available and has processed in the last two decades from IRI-2001. It is continuously updated and has many versions, including IRI-2001 (Bilitza, 2001), IRI-2007 (Bilitza & Reinisch, 2008), IRI-2012 (Bilitza et al., 2014), and IRI-2016 (Bilitza et al., 2017). Among them, IRI-2016 is the latest version for IRI model, which 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, mainly. In this model, the F layer peak region parameter is estimated by URSI (Szaszczewicz et al., 1998) or Consultative Committee for International Radio (CCIR) 1966 (CCIR, 1967) model. The URSI model is recommended over the oceans and the CCIR model over the continents. Then, the bottom-side and top-side vertical electron density of the model can be obtained by different formulations. The model uses an extrapolation of the topside function up to the user-specified height. Thus, the obtained vertical electron density profile can be used to compute the TEC values by integrated up to a given altitude. The main input parameters include location,
time, date, solar indices, magnetic index, ionospheric index, and altitude range. Based on the input parameters, we can obtain the electron density, electron temperature, ion temperature, ion composition, equatorial vertical ion drift, VTEC, F1 probability, spread-F probability, auroral boundaries, and effects of ionospheric storms on F and E peak densities. In this study, the URSI model and NeQuick options for the topside profile estimation are considered. The default ABT-2009 option for the bottom-side thickness shape parameter is used. The altitude range is from 50 to GPS satellite altitude, for example, 20,200 km.

NeQuick model is used to correct ionospheric delays for the Galileo satellite system. It was developed based on the Di Giovanni-Radicella (DGR) proposed by Di Giovanni and Radicella, which is designed for trans-ionospheric propagation applications (Giovanni & Radicella, 1990). It is a 3D ionospheric model, which can be used to derive TEC along the arbitrary ray from receiver to satellite. To describe the electron density of the ionosphere up to the peak of the F2 layer, the NeQuick uses a profile formulation, which includes five semi-Epstein layers with modeled thickness parameters. The shape of Epstein layer in NeQuick model is determined by the parameters derived from the International Telecommunication Union Radio communication sector (ITU-R) coefficients (formerly called CCIR), for example, peak ionization, peak height, and semi-thick (Nava et al., 2008; Radicella, 2009). It has been updated from NeQuick1 (Hochegger et al., 2000; Radicella & Leitinger, 2001) to NeQuick2 (Nava et al., 2008). Besides, the limitation of F10.7, that is, from 64 to 193 Solar Flux Unit (SFU), has been eliminated in NeQuick2 model (Memarzadeh, 2009). Compared with NeQuick1 model, NeQuick2 model has the same model structure but a better description of the bottom- and top-side ionosphere (Coïsson et al., 2006; Leitinger et al., 2005; Nava et al., 2008) and introduces a new geomagnetic latitude file. The inputs are position, time, and solar flux. Based on the inputs, we can obtain the electron concentration at the given location and time mainly. In this study, the altitude range is the same with IRI-2016 model.

![Figure 1. Solar condition for the experimental period.](image)

### Table 1

| Item                                    | Strategies                                                                 |
|-----------------------------------------|---------------------------------------------------------------------------|
| Satellite Positioning mode              | GPS                                                                       |
| Sampling rate                           | Static                                                                    |
| Elevation cutoff                        | 30 s                                                                      |
| Station coordinates                     | IGS weekly SINEX products                                                 |
| Satellite orbit and clock               | Fixed to GFZ final products                                               |
| Tropospheric delay                      | Initial model + random walk model + global mapping function (Böhm et al., 2006) |
| Tropospheric gradients                  | Random walk model                                                         |
| Phase-windup effect                     | Corrected                                                                 |
| Receiver clock                          | Estimated as white noise                                                  |
| Satellite and receiver antenna phase center | IRI-2016/NeQuick2/IGSG + modified single layer mapping function (Schaer, 1999) |
Figure 2. Distribution of experimental GNSS monitoring stations used for validation of different ionosphere models.

Figure 3. Differences between IRI-2016 and IGSG on different solar condition days.
The Ionosphere Working Group of the IGS (Iono-WG) was created in 1998 to generate reliable VTEC maps by ground-based TEC measurements of GNSS. There are seven Ionosphere Associate Analysis Centers (IAACs) providing GIMs recently, which are generated by corresponding global mapping techniques using ground-based GNSS observation (Roma-Dollase et al., 2018). Generally, the IGSG is a product with higher reliability, which is generated by the combination of GIMs provided by Center for Orbit Determination in Europe (CODE), Universitat Politècnica de Catalunya/IonSAT (UPC), European Space Operations Center of European Space Agency (ESA), and Jet Propulsion Laboratory (JPL) using weighted mean method determined by self-consistency test (Hernández-Pajares et al., 2017; Roma-Dollase et al., 2018).

3. Methods and Data Collections

In this section, the introduction of assessment methods is introduced first, followed by the data collections for model performance evaluation. Finally, the accuracy index used to reflect the assessment accuracy is presented.
3.1. VTEC-Altimeter Assessment Method

The VTEC data over the oceanic region can be obtained from Jason satellite onboard dual-frequency altimeter observations, which indicates that Jason measurements are independent with ground-based GNSS data and can be used to validate the performance of different ionospheric models over the oceanic region. The onboard altimeter contains two frequencies observations, including a Ku-band (13.575 GHz) as the primary frequency and a C-band (5.3 GHz) as auxiliary frequency (Lambin et al., 2010). Generally, the Jason series satellites move from about 65°S to 65°N and cover only the oceanic regions during its repeat cycle. Therefore, it is an excellent choice for the assessment over the oceanic region where the GNSS-based
observations are sparse. The Jason VTEC data can be extracted from the vertical phase ionospheric delay provided in Ku-band frequency as shown:

\[ VTEC = -\frac{dR_f_{Ku}}{40.3} \]  

where \( dR \) is Ku-band ionospheric range correction, \( f_{Ku} \) is Ku-band frequency in GHz. In this study, we use a 21 s smoothing window to reduce the inherent noise effects of the altimeter (Imel, 1994).

3.2. Assessment Based on dSTEC Method

The ionospheric observations derived from GNSS dual-frequency measurements can be used to assess the ionospheric models over continents. There are two methods to obtain ionospheric observables for evaluation: (1) Slant TEC (STEC) derived from geometry-free combinations of code and carrier phase measurements, named carrier-to-code leveling (CCL) (Komjathy, 1997; Mannucci et al., 1998); (2) STEC directly calculated with carrier phase measurements only. However, the STEC derived from CCL suffers from leveling errors, and the correction errors of DCBs significantly (Ciraolo et al., 2007). Due to lower noise and multipath effects for carrier phase, STEC derived from the difference of carrier phase can be an excellent reference measurement to validate ionospheric models (Hernández-Pajares et al., 2017; Orus et al., 2005, 2007). In general, dSTEC is defined as the difference between STEC at each epoch within a phase-continuous arc and that of the highest elevation in the same arc, which can achieve accuracy better than 0.1 TECU and will be free from the ionospheric assumptions or model errors (Feltens et al., 2011). The detailed description of dSTEC method can be found in early studies (Hernández-Pajares et al., 2017; Ren et al., 2019). Therefore, the dSTEC method is employed to evaluate the accuracy of IRI-2016 and NeQuick2 models as well as IGSG.

3.3. SF-PPP Assessment Method

Ionospheric delay is the main error source that can affect the positioning accuracy of SF-PPP. Hence, SF-PPP is an appropriate way to
assess the quality of different ionospheric models. In this study, the detailed SF-PPP processing strategies are summarized in Table 1.

### 3.4. Data Collections

In order to present statistical results comprehensively, the performances of IRI-2016, NeQuick2, and IGSG are evaluated from Day of Year (DOY) 001, 2002 to DOY 365, 2018, which cover at least one solar cycle. As is shown in Figure 1, the experimental period starts from higher solar activity year (2002) to lower solar activity year (2018). The red lines during the year of 2015 denote the experimental period for the assessment by SF-PPP method. The distribution of the selected stations is plotted in Figure 2. In Figure 2, the red circles denote the stations used to assess the quality of different ionospheric models using dSTEC assessment method; blue squares are the stations used to determine the quality of different ionospheric models using SF-PPP technique; green pentacles are the stations used to generate IGSG. As we can see, the validation stations, which are not used to generate IGSG products, distributed evenly covering the continents, oceans, and polar regions.

Figure 8. The accuracy of different ionospheric models for each year.

Figure 9. Mean bias and RMS values of different latitudes for IRI-2016, NeQuick2, and IGSG relative to Jason2/3 VTEC.
4. Results and Discussion

4.1. Consistency and Differences of IRI-2016, NeQuick2, and IGSG

IGSG is one of the best ionospheric products with higher accuracy and reliability relative to individual GIMs used in the combination, which indicates that it is an excellent product to assess the consistency with different ionospheric models. Therefore, it is selected as a reference to evaluate the consistency of different ionospheric models and calculate the differences between IRI-2016, NeQuick2, and IGSG.

Figures 3 and 4 show the results of the differences of IRI-2016, NeQuick2 relative to IGSG on solar high-level day (DOY 004, 2014) and solar low-level day (DOY 362, 2018), respectively. As we can see, the differences of IRI-2016 and NeQuick2 compared with IGSG on solar high-level day are larger than that on solar low-level day. On solar high-level day, the VTEC values derived from IRI-2016 are smaller than that of IGSG over most regions. The values of NeQuick2 are larger than IGSG over most areas. The biases mainly range from $-10$ to $10$ TECU, while their maximum can be larger than 30 TECU over the equatorial ionization anomaly (EIA) regions. On solar low-level day, the differences of IRI-2016 and NeQuick2 are nearly the same compared with IGSG over most regions. The biases are mainly between $-5$ and $5$ TECU. The maximums of the two ionospheric models appear over the EIA regions, which can reach about 10 TECU.

The variation of hourly mean bias of the IRI-2016 and NeQuick2 every 2 hr of local time (LT) relative to IGSG is plotted in Figure 5. As we can see, these two ionospheric models have a similar performance. The maximum bias mainly occurred between 12:00 and 16:00 LT. The hourly mean biases mainly range from $-5$ to $5$ TECU for low-solar condition years, and the absolute biases are larger than $5$ TECU for low-solar condition years between 12:00 and 16:00 LT. It will exceed 15 TECU for the days with high-solar conditions, especially between 12:00 and 16:00 LT.

4.2. Comparison With VTEC-Altimeter

The distribution of mean bias for IRI-2016, NeQuick2, and IGSG relative to Jason2/3-VTEC during the tested period globally is shown in Figure 6. In Figure 6, the gray parts denote that there are no VTEC values derived from Jason2/3 satellites over the corresponding parts. As we can see, the continents also have Jason2/3 ionospheric data, which is caused by the reflection of continental ice, enclosed seas or lakes, and heavy rain over corresponding regions. The biases for IRI-2016 and NeQuick2 relative to VTEC of Jason2/3 VTEC are smaller than that of IGSG. For the biases of IRI-2016 and NeQuick2 relative to Jason2-VTEC, they range from $-5$ to 0 TECU over most areas, while the biases are 2.5 to 7.5 TECU relative to Jason3-VTEC. The maximum biases appear over the EIA region compared with Jason2-VTEC and Jason3-VTEC with a maximum bias of 7.5 TECU. For the biases of IGSG, IRI, and NeQuick2 relative to Jason3-VTEC, they have similar trends for corresponding models and are 3 TECU larger than that of Jason2-VTEC.

The time series of daily mean bias and RMS for IRI-2016, NeQuick2, and IGSG relative to Jason2/3-VTEC are shown in Figure 7. The results show that the performance of NeQuick2 is slightly better than that of IRI-2016 over the oceanic region. The bias sequences of IGSG
show a periodic term with relative to Jason2/3-VTEC while those of IRI-2016 and NeQuick2 do not have. The daily mean bias of IGSG mainly ranges from 2.0 to 6.0 TECU for Jason2-VTEC, while it is about 4.0 to 7.0 TECU for Jason3-VTEC. Besides, it is about −4.0 to 5.0 TECU for IRI-2016 and NeQuick relative to Jason2-VTEC, while that is 2.0 to 7.0 TECU with relative to Jason3-VTEC. The RMS sequences of IRI-2016 and NeQuick2 are larger than those of IGSG for Jason2-VTEC. With relative to Jason3-VTEC, the RMS sequences of IRI-2016 and NeQuick2 are mainly smaller than that of IGSG. The statistical results are listed in Table 2.

As we can see, the performance of the NeQuick2 is slightly better than that of IRI-2016 over the oceanic region but worse than that of IGSG. The mean bias of IGSG is 3.4 and 5.4 TECU relative to Jason2-VTEC and Jason3-VTEC, respectively. The mean bias of IRI-2016 and NeQuick2 relative to Jason2-VTEC is smaller, for example, about 2.6 TECU, than that of IGSG, while it is about 1.4 TECU between IGSG and empirical models for Jason3-VTEC. The mean RMS values are 4.8 and 6.0 TECU for IGSG and empirical models with relative to Jason2-VTEC, while the corresponding values are 5.4 and 6.0 TECU with relative to Jason3-VTEC.

To understand the accuracy of the models each year over the oceanic region, the daily mean bias and RMS of each year relative to Jason2/3-VTEC are plotted in Figure 8. As we can see, the mean bias and RMS of IGSG have a good agreement with the solar condition. However, the trend of daily mean bias for the empirical models is different from that for IGSG. The yearly mean biases of IGSG range from 2 to 5 TECU relative to Jason2-VTEC and 5 to 6 TECU relative to Jason3-VTEC, respectively. The annual mean biases of the empirical models are between −1 and 2 TECU and 3.5 to 4.5 TECU relative to Jason2-VTEC and Jason3-VTEC, respectively. Meanwhile, the yearly mean biases are negative in 2011 and 2014 for IRI-2016, and in 2012, 2013, and 2015 for NeQuick2, indicating that the empirical models underestimate the TEC values over the oceanic region when the magnitude of solar conditions is in high level. For the empirical models, the mean RMS sequences also have a good agreement with the solar condition.

The performances of IRI-2016, NeQuick2, and IGSG over different latitude regions with a bin width of two degrees for the available period of Jason2/3 satellites are shown in Figure 9. As we can see, all three models have a typical U shape variation, and the IGSG is significantly better than the other two empirical ionosphere models. The mean bias of IGSG ranges from 1.0 to 6.0 TECU and 3.5 to 7.5 TECU relative to Jason2-VTEC and Jason3-VTEC, while the corresponding bias is 3.0 and 1.0 TECU larger than that of empirical models. In terms of RMS, the values of IRI-2016 and NeQuick2 are nearly the same, which are larger than those of IGSG. The RMS values are between 3.0 and 10.0 TECU for empirical models, 3.0 and 7.5 TECU for IGSG, and 3.0 and 9.0 TECU for empirical models, 4.0 and 8.0 TECU for IGSG relative to Jason2-VTEC and Jason3-VTEC.

| Model   | Bias | RMS  |
|---------|------|------|
| IGSG    | 0.3  | 1.8  |
| IRI-2016| −0.3 | 2.7  |
| NeQuick2| −0.3 | 2.6  |

Table 3. Statistical Results of the dSTEC Method from 2002 to 2018 (Unit: TECU)

Figure 12. Mean bias and RMS of the three ionospheric models for selected stations using the dSTEC method during the experimental period. Top: mean bias; bottom: RMS.
4.3. Assessment With dSTEC Method

The distribution of validated stations used to assess the performance of IRI-2016, NeQuick2, and IGS models by dSTEC assessment method is shown in Figure 2 with red circles. The time series of daily mean bias and RMS sequences of validation results for different models during the experimental period are plotted in Figure 10. It shows that the IGS model is better than the empirical models, while the performances of IRI-2016 and NeQuick2 are nearly the same. The daily mean bias time series of IGS model is more stable than that of the IRI-2016 and NeQuick2. The performance of IRI-2016 and NeQuick2 is slightly worse than that of IGS during low solar condition years, while it is significantly worse than IGS during high solar condition years. The daily mean bias of IGS mainly ranges from −1.0 to 1.0 TECU, while it is about −2.0 to 1.0 TECU for IRI-2016 and NeQuick2. The RMS values of IGS are smaller than the other two models, and the RMS sequences of the three models have a periodic term, which is related to the solar condition (Hernández-Pajares et al., 2009; Schaer, 1999) and the interannual variation of ionosphere. The RMS values range from 0.0 to 6.0 TECU and 0.0 to 8.0 TECU for IGS and empirical models.

The variation of mean bias and RMS of the three models each year is plotted in Figure 11, and their statistical results are listed in Table 3. As is shown in Figure 11, IGS model performs better than the other two models, and the performances of the empirical models are nearly the same. The yearly mean bias on solar condition high-level years is larger than that on other solar condition years for IGS. The annual mean biases of the empirical models are negative from 2002 to 2017 and 2002 to 2016 for IRI-2016 and NeQuick2, respectively. The yearly mean biases mainly range from −1.0 to 0.0 TECU for IRI-2016 and NeQuick2, while it is 0.0 to 0.8 TECU for IGS. In terms of RMS, all three models have a similar variation, which is related to the solar condition. From Table 3, we can find that the mean biases are 0.3, −0.3, and −0.3 TECU for IGS, IRI-2016, and NeQuick2, respectively. The values of RMS are about 1.8, 2.7, and 2.6 TECU for IGS, IRI-2016, and NeQuick2.

The statistical results of each station using the dSTEC assessment method are plotted in Figure 12. As we can see, IGS model performs better than IRI-2016 and NeQuick2 ionospheric models, while the performances of IRI-2016 and NeQuick2 are nearly the same. For the three models, the performance over the high latitude is better than that over the low latitude. It also shows a significant equatorial ionization anomaly. The RMS for two empirical models can reach 6 TECU over the low-latitude stations.

4.4. SF-PPP Performance

SF-PPP solution is used to evaluate the ionospheric corrections corrected by different kinds of ionospheric models. The experimental period is from DOY 171, 2014 to DOY 270, 2014, which covers solar low-level condition, solar moderate-level condition, and solar high-level condition (the red part in Figure 1). The selected stations are listed in Figure 2 with blue squares. The detailed processing strategies for SF-PPP solution are listed in Table 1.

The daily mean 3D positioning error corrected by different ionospheric models is presented in Figure 13. The positioning accuracy can reach 1.0 m in 3D direction for the three ionospheric models. Among the three models, the positioning accuracy corrected by IGS is the best, then follows NeQuick2. The positioning accuracy corrected by IRI-2016 is the worst. The positioning errors mainly range from 0.8 to 1.8 m during the experimental days. Their maximum errors are about 1.60, 2.80, and 2.20 m for IGS, IRI-2016, and NeQuick2, respectively. The mean positioning error is 1.06, 1.30, and 1.15 m for IGS, IRI-2016, and NeQuick2, respectively. The horizontal positioning accuracy is listed in Table 4. As we see, the positioning accuracy of IGS is 0.17 m in the horizontal direction, which is better than that of IRI-2016 and NeQuick2. The
performances of IRI-2016 and NeQuick2 models on the positioning domain are the same, which are about 0.50 m.

5. Conclusion

In this study, the accuracy and reliability of two commonly used 3D empirical ionosphere models, that is, IRI-2016 and NeQuick2, and a widely used two-dimensional ionosphere model, that is, IGSG, have been assessed by different methods from 2002 to 2018.

The experimental results compared with IGSG show that the values of IRI-2016 and NeQuick2 are generally smaller than IGSG. Compared with IGSG, the biases mainly range from −10 to 10 TECU, while they are between −5 and 5 TECU on solar low-level days for empirical models. Their maximum mainly appears over the EIA regions.

In terms of the ionosphere over the oceanic region, IGSG is slightly better than IRI-2016 and NeQuick2, while the performance of the empirical models is nearly the same. The biases for IRI-2016 and NeQuick2 models relative to Jason2/3-VTEC are smaller that of IGSG. The daily mean biases are about 2.0 to 6.0 TECU with relative to Jason2-VTEC and 4.0 to 7.0 TECU for IGSG with relative to Jason3-VTEC, respectively, while the corresponding daily mean biases are −4.0 to 5.0 TECU and 2.0 to 7.0 TECU for IRI-2016 and NeQuick2. The mean RMS values are 4.8 and 6.0 TECU for IGSG and empirical models with relative to Jason2-VTEC while the values are 5.4 and 6.0 TECU with relative to Jason3-VTEC.

In terms of test results by dSTEC assessment method, the mean bias of IGSG mainly ranges from −1.0 to 1.0 TECU, while it is about −2.0 to 1.0 TECU for the IRI-2016 and NeQuick2. The RMS values of IGSG are smaller than those of the empirical models. All of them have a periodic term. The yearly mean bias ranges from −1.0 to 0.0 TECU mainly for IRI-2016 and NeQuick2, while it is 0.0 to 0.8 TECU for IGSG. The mean biases are 0.3 and −0.3 TECU for IGSG and empirical models, respectively. The RMS values are about 1.8 and 2.6 TECU for IGSG and empirical models, respectively. The performance over the high latitude is better than that over the low latitude. The RMS values for the empirical models can exceed 6 TECU over the low-latitude stations.

The SF-PPP assessment results show that the positioning accuracy corrected by the three models can reach 1 m in 3D direction. Their maximum values are about 1.60, 2.80, and 2.20 m for IGSG, IRI-2016, and NeQuick2, respectively. The positioning accuracy corrected by IGSG is 0.17 m in the horizontal direction, which is better than that of IRI-2016 and NeQuick2 ionospheric models with an accuracy of about 0.50 m.

From the analysis above, we can find that both of the two empirical models underestimate the TEC values. These two models have similar statistical results but with a slight difference. Since both models use the same formalism for the topside and above, they have similar statistical results. However, the input F10.7 value is daily, 81 days, and 12 months running mean for IRI-2016 while that for NeQuick2 is daily. Meanwhile, the IRI model uses the URSI model for the F peak density while NeQuick2 uses CCIR model in this study. Therefore, the difference of input F10.7 value and the model for F peak density calculation could lead to the different TEC estimates of IRI-2016 and NeQuick2 ionospheric models. On the other hand, they are both empirical models based on historical observation data and formulated based on the monthly median parameter. Hence, they can reflect the long-term average condition of the ionosphere, but the TEC values derived from them are always smaller than those from different methods.

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