The Spatial and Temporal Analysis of Hourly TECs Derived From Selected Representative Ionospheric Climatology Models

Junchen Xue, Lin Quan, and Wenyao Zhu

Abstract – In this study, the TECs derived from three well-established climatology models including IRI-2012 (International Reference Ionosphere), SPIM-2014 (Standard Plasmasphere-Ionosphere Model), and NIC09 (New Ionosphere Climatology) were evaluated with IGS final TEC maps in spatial and temporal domains. It was found that NIC09 overestimated TECs slightly with respect to IGS results. The RMSE over all seasons was about 4 TECu. That was greater in winter than in other seasons. SPIM-2014 overestimated TECs greatly. There were spring and autumn anomalies, with the autumn anomaly more obvious. The RMSE was approximately 8 TECu. IRI-2012 underestimated TECs during all seasons except in autumn. The RMSE was nearly 7 TECu except in winter. In terms of the latitude dependence, the performance of the three models was better in middle and high latitudes than in low latitudes (especially equatorial regions). The performance of NIC09 was generally the best, followed by IRI-2012 and SPIM-2014. The performance of IRI-2012 was mostly better than SPIM-2014 except in summer in the northern hemisphere and winter in the southern hemisphere. The finding in this study could provide references for the specific application of ionospheric climatology models.

1. Introduction

Ionospheric effect is the main error source in global navigation satellite system (GNSS) based measurements. Ionospheric climatology models can be used for providing the related key parameters in terms of electron density or total electron content (TEC). Many studies have introduced various ionospheric climatology models and discussed their performance (see [1–12]). However, the performance of three ionospheric climatology models (IRI-2012 (International Reference Ionosphere) [5], SPIM-2014 (Standard Plasmasphere-Ionosphere Model) [6], and NIC09 (New Ionosphere Climatology) [7]) in high-time resolution, especially on an hour scale, has been much less studied.

In this study, the hourly TECs derived by three ionospheric climatology models were analyzed comprehensively. The performance of those models in spatial and temporal domains were qualified with respect to IGS final ionospheric products.

2. Methodology

The performance of the three ionospheric climatology models IRI-2012, SPIM-2014, and NIC09 were investigated in this study. Input parameters for IRI-2012 and SPIM-2014 were set the same (storm model and the parameters recommended by URSI (Union Radio-Scientifique Internationale)). Input parameters for NIC09 were only the time and location.

For the spatial domain, the global region was divided into grids with 5-degree intervals from longitude –180 degrees to 180 degrees and 2.5-degree intervals from latitude –87.5 degrees to 87.5 degrees. For the temporal domain, the epoch ranges covering equinoxes (spring and autumn) and solstices (summer and winter) in the high solar activity year of 2013 were selected. Four time spans surrounding those critical time periods were further chosen: day of year (DOY) 077–081, 170–174, 263–267, and 353–357. For each day, TECs of global grids were computed for each epoch with 2-h intervals from UT 0 to 22.

The TECs derived from the three models were compared with the references from IGS final ionospheric maps [13] which are known to be highly reliable for global regions [14]. The statistical indices were bias and root-mean-square error (RMSE). The equations for calculating those indices are as follows:

$$\text{bias} = <\Delta\text{TEC}_i>$$

$$\text{RMSE} = \sqrt{<\Delta\text{TEC}_i^2>}$$

$$\Delta\text{TEC}_i = \text{TEC}_{\text{mdl},i} - \text{TEC}_{\text{ref},i}\,, \quad i = 1, n \qquad (1)$$

where $< >$ is the average of the variable, $\text{TEC}_{\text{mdl},i}$ is the model TEC, $\text{TEC}_{\text{ref},i}$ is the reference, and n is the total number of samples.

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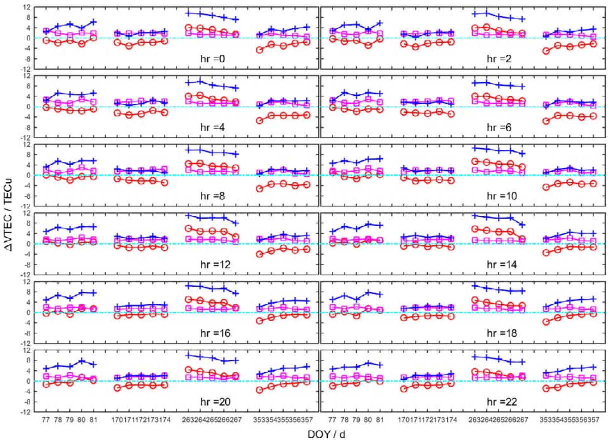

Figure 1. Biases of the three models in temporal domains. (The *x*-axis is DOY, unit: day. The *y*-axis is bias, unit: TECu. hr is UT epoch. Pink square for NIC09 model, blue cross for SPIM-2014 model, and red circle for IRI-2012 model. The cyan dash line represents the zero offset.)

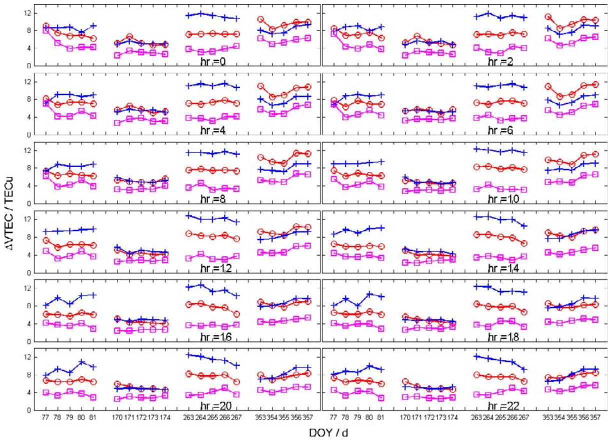

Figure 2. RMSE of the three models in temporal domains. (The *x*-axis is DOY, unit: day. The *y*-axis is RMSE, unit: TECu. hr is UT epoch. Pink square for NIC09 model, blue cross for SPIM-2014 model, and red circle for IRI-2012 model. The cyan dash line represents the zero offset.)

3. Results and Discussion

3.1 Performance of Models in the Temporal Domain

To investigate the temporal characteristics of the three models, the performance for 12 epochs was assessed. The statistics were performed for each equinox and solstice respectively. Figures 1 and 2 show the bias and RMSE for the models during different seasons. From the bias plot, systematic offsets for models are compared with IGS results. NIC09 is closest to IGS with a tiny positive bias of nearly 2 TECu. The biases are not affected by seasons. SPIM-2014 overestimates TECs. The biases in spring and autumn are larger than other seasons. Spring and autumn anomalies are seen, with autumn more noticeable. IRI-2012 underestimates TECs during all seasons except autumn. There is an underestimate in winter.

In terms of RMSE (Figure 2), the performance of three models in summer is better than in other seasons. The RMSE of NIC09 is roughly 4 TECu within the whole year except in winter, which is the smallest among models. The RMSE of SPIM-2014 is approximately 9 TECu with larger values in spring and autumn. In particular, the RMSE could arrive at about 12 TECu in autumn. The RMSE of IRI-2012 is mostly under 8 TECu. The RMSE of IRI-2012 is lower than that of SPIM-2014 during the whole year except in winter. Furthermore, the RMSE of IRI-2012 seems more stable with respect to that of SPIM-2014.

The comprehensive statistics are shown in Table 1. From the table, the biases of NIC09 are the smallest, which is approximately 2 TECu. The biases keep stable within the year, and there are no seasonal anomalies. The RMSE is in the level of about 4 TECu. That is worse in winter than in other seasons. The biases for SPIM-2014 are roughly 5 TECu. There are spring and autumn anomalies with the autumn anomaly more prominent. The RMSE is nearly 8 TECu over all seasons. The underestimates of TECs for IRI-2012 are obvious within the year except in autumn, which is consistent with the discussions for different versions of IRI (see [7, 10, 12]). The RMSE is almost 7 TECu except in winter. Overall, the performance of NIC09 in temporal domain is the best among the three models. The reason might be related to the fact that NIC09 is established based on JPL GIM (global ionosphere maps) (see [7]). In addition, comparing with the indices of different hourly epochs, the difference is not obvious. It appears that it is not favorable to derive the TECs in hourly resolution by climatology models at present. This may be attributed to the lack of the data source from networks and the inner algorithm in the software.

3.2 Performance of Models in the Spatial Domain

The spatial correlation of the ionosphere is highly dependent on the latitude. The principal characteristics are dominated by the equatorial fountain or equatorial anomaly. To investigate the performance of the models in spatial domain, the hourly computed TECs were evaluated along different latitudinal zones. Based on Section 3.1, the differences of statistical indices between different epochs are not obvious. Therefore, only the statistics for UT 0 are shown in this section as seen in Figure 3. From the figure, the bias and RMSE of all models are better in middle and high latitudes (> 60 degrees) than in low latitudes (< 30 degrees). There are equatorial anomalies, which should be related to the complex changes of ionosphere near the equator. From the left subplot, the biases of NIC09 are the smallest. The model is a little overestimated except in winter in the southern hemisphere. SPIM-2014 is mostly overestimated except in summer in the northern hemisphere

Table 1. The statistical indices of three models in temporal domains (IRI for IRI-2012, SPM for SPIM-2014, NIC for NIC09; SS for season; number 1–4 for spring, summer, autumn, and winter, respectively; unit: TECu)

HR	Bias				RMSE			
UT	SS	IRI	SPM	NIC	SS	IRI	SPM	NIC
0	1	−1.15	4.49	1.94	1	7.32	8.54	5.08
	2	−1.84	1.89	1.81	2	5.31	5.12	2.85
	3	2.91	8.54	1.31	3	7.22	11.27	3.67
	4	−2.71	3.06	0.99	4	9.58	8.21	5.76
2	1	−1.12	4.44	2.01	1	7.28	8.50	4.81
	2	−2.17	1.62	1.80	2	5.43	5.23	2.86
	3	2.97	8.47	1.33	3	7.20	11.23	3.68
	4	−3.21	2.49	1.08	4	10.02	8.30	5.74
4	1	−1.05	4.44	2.04	1	7.32	8.58	4.96
	2	−2.46	1.37	1.95	2	5.61	5.37	3.19
	3	3.09	8.45	1.43	3	7.28	11.19	3.71
	4	−3.77	1.85	1.15	4	10.01	7.81	5.66
6	1	−1.01	4.47	1.95	1	7.12	8.45	5.01
	2	−2.40	1.44	2.06	2	5.41	5.29	3.44
	3	3.21	8.51	1.42	3	7.29	11.05	3.75
	4	−4.01	1.57	1.06	4	10.24	7.89	5.68
8	1	−0.72	4.83	1.81	1	6.61	8.37	4.66
	2	−2.10	1.68	1.95	2	5.07	5.14	3.33
	3	3.77	9.05	1.51	3	7.56	11.45	3.57
	4	−3.90	1.68	1.19	4	10.32	8.03	5.65
10	1	−0.06	5.49	1.74	1	6.63	9.13	4.41
	2	−1.73	1.94	1.78	2	4.70	4.94	2.95
	3	4.45	9.62	1.54	3	8.06	11.93	3.37
	4	−3.46	2.02	1.38	4	10.05	8.18	5.44
12	1	0.45	6.03	1.76	1	6.37	9.46	4.03
	2	−1.16	2.42	1.52	2	4.36	4.86	2.67
	3	4.69	9.83	1.45	3	8.25	12.10	3.41
	4	−2.63	2.77	1.61	4	9.44	8.34	5.06
14	1	0.71	6.41	1.67	1	6.04	9.43	3.75
	2	−0.80	2.73	1.50	2	4.15	4.77	2.53
	3	4.45	9.69	1.21	3	7.95	11.91	3.38
	4	−1.83	3.57	1.59	4	8.86	8.59	4.76
16	1	0.52	6.44	1.71	1	6.07	9.41	3.66
	2	−0.84	2.71	1.42	2	4.37	4.80	2.51
	3	3.80	9.23	1.33	3	7.68	11.58	3.59
	4	−1.59	3.88	1.42	4	8.51	8.76	4.73
18	1	0.15	6.26	1.67	1	6.29	9.26	3.64
	2	−1.51	2.08	1.77	2	4.74	4.72	2.95
	3	3.40	9.04	1.31	3	7.72	11.64	3.88
	4	−1.57	4.15	1.44	4	8.06	8.65	4.62
20	1	−0.16	6.09	1.56	1	6.55	9.21	3.59
	2	−1.81	1.85	1.64	2	5.09	4.82	2.86
	3	3.04	8.80	1.28	3	7.62	11.43	3.88
	4	−1.56	4.41	1.57	4	7.67	8.29	4.71
22	1	−0.57	5.74	1.55	1	6.57	8.87	3.81
	2	−1.73	2.00	1.49	2	5.23	5.05	2.82
	3	2.58	8.32	1.48	3	7.43	10.97	4.04
	4	−1.48	4.45	1.53	4	7.81	7.96	4.95

and winter in the southern hemisphere. The IRI-2012 underestimates TECs except autumn and winter in the northern hemisphere. From the right subplot, the RMSE of NIC09 is the smallest and almost not correlated with the latitude in summer. The RMSE of SPIM-2014 is the greatest among three models except in summer in the northern hemisphere and winter in the southern hemisphere. The RMSE of IRI-2012 is smaller than the SPIM-2014 except in summer in the northern hemisphere and winter in the northern hemisphere. Generally, the performance of NIC09 in spatial domain is the best, followed by IRI-2012 and SPIM-2014.

4. Conclusions

The performance of three climatology models in terms of derived hourly TECs was investigated in this study. The evaluation was performed in the spatial (latitudinal zones) and temporal domain (different equinoxes and solstices). From the results, the performance of NIC09 is the best, which suggests the model could be selected for the ionospheric correction in Space Geodesy applications. It should be noted that the best performance may be attributed to the fact that NIC09 is established based on JPL GIM. There are seasonal and latitudinal characteristics taking account of

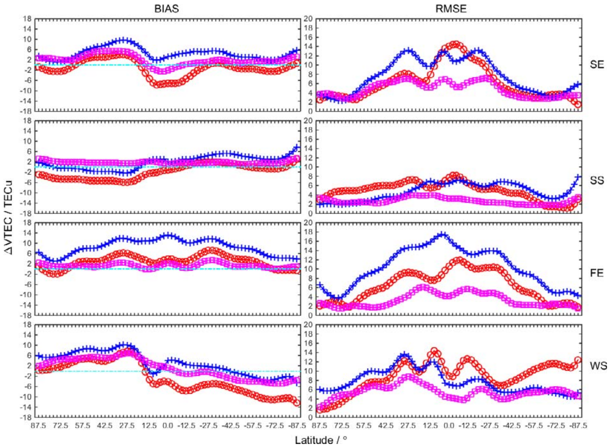

Figure 3. Statistical indices for three models along various latitudinal zones. (Left subplot is bias, right subplot is RMSE. x-axis is latitude, unit: degree. y-axis is statistical values, unit: TECu. SE for spring equinox, SS for summer solstice, FE for autumn equinox, WS for winter solstice. Pink square for NIC09 model, blue cross for SPIM-2014 model, and red circle for IRI-2012 model. The cyan dash line represents the zero offset.)

the statistics. Additionally, no noticeable differences are seen for the statistics of different hourly epochs. That indicates the hourly resolution for the TEC calculation is insufficient to be derived by ionospheric climatology models at present.

On the other hand, NIC09 could provide only TECs although the performance of its hourly computed TECs was the best. SPIM-2014 and IRI-2012 could, however, produce more parameters (such as electron density and temperature) besides TECs. That could be more available in the related studies of space weather. Furthermore, the performance of three models in terms of derived hourly TECs could also be studied in the local time and geomagnetic domains.

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