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Performance Evaluation of Global Ionospheric Models with Indian Regional Navigation Data over Low Latitude Station during Low Solar Activity Year 2017

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Abstract—This paper discusses the variation of ionospheric Total Electron Content (TEC) over low latitude Indian region, Hyderabad station (Lat: 17.39° N, Lon: 78.31° E) for geomagnetic quiet and disturbed days during the low solar activity period (2017 year) of the 24th solar cycle using global ionospheric models and experimental NavIC (Navigation with Indian Constellation) data. The work mainly focuses on the performance of the IRI Plas 2017 (International Reference Ionosphere) model with and without assimilation of TEC input, GIM TEC (Global Ionospheric Maps) and IRI 2016 models. In order to evaluate the performance of the models, the diurnal, monthly, and seasonal variations of Vertical TEC (VTEC) are predicted and compared with Indian regional NavIC data. From the result analysis it is observed that smaller Root Mean Square Errors (RMSEs) between NavIC VTEC and modelled VTEC are found in June and December solstice months than March and September equinox months. The VTEC predicted by the IRI Plas with assimilation of TEC input option produced smaller estimation errors than IRI Plas without assimilation of TEC input and IRI 2016 model. The same analysis has been tested for geomagnetic storm occurred during 7–9 September, 2017 for different locations. The IRI Plas 2017 with TEC input option exhibits better performance than IRI Plas and IRI 2016 models. Therefore, the VTEC predictions by assimilation of optional inputs will be helpful in applications of ionspheric studies to predict the dynamics in the ionosphere particularly for the period of disturbed geomagnetic conditions.

1. INTRODUCTION

The NavIC/IRNSS (Indian Regional Navigation Satellite System) with 7 satellites constellation was developed by Indian Space Research Organization (ISRO). The NavIC system covers India and a range of 1,500 km beyond its borders. It can provide position accuracy within 10 m over the Indian landmass and less than 20 m over the oceans. It is expected to provide better coverage area and improved accuracy with satellite constellation enhanced to 11 satellites. In the present constellation four satellites are geosynchronous (1A, 1B, 1D, 1E), and the remaining is geostationary (1C, 1F, 1G). The IRNSS satellites are placed in the orbits at the height of 36,000 km from the earth. The NavIC operates in L5 (1176.45 MHz) and S1 (2492.028 MHz) frequencies [1]. Any regional or global navigation system performance is degraded by several sources of errors such as satellite orbital error, clock error, multipath effects, satellite and receiver biasing, Dilution of Precision, tropospheric error, and ionospheric error. Among them ionospheric error is the predominant source of error. This error is directly proportional to the TEC present in the ionosphere. The ionospheric propagation effects play a critical role on the performance of Communication, Navigation, and Surveillance (CNS) system applications. Precise

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estimation of TEC would be very helpful in improving the system performance in both civilian aviation and defence applications. The low latitude ionospheric regions are highly dynamic in nature due to several phenomena such as equatorial ionospheric anomaly (EIA) [2] and scintillations, which can result in variations of different parameters such as TEC. These TEC variations affect navigation and communication to a great extent. Hence, new investigations in understanding and modelling of dynamic ionospheric variations over low latitude regions are necessary. The ionospheric models can be classified as global, regional, and local for estimating ionospheric characteristics of a specific region at a specific time, latitude, longitude, altitude, and geomagnetic activity. In the recent past, several regional ionospheric models have been investigated over the Indian region with GPS data [3–5]. Significant fluctuations in TEC response have been observed by various investigations carried out during different geomagnetic storms and solar cycle phases over low-latitude and equatorial regions using GPS data [6–13].

The IRI model is one of the most widely used global empirical model to predict the behaviour of the ionospheric layer in terms of various parameters. The ionospheric parameters from IRI model are based on the worldwide data available from ground based as well as space based system. The IRI model is a joint project, which is developed by the Committee on Space Research (COSPAR) and International Union of Radio Science (URSI). The IRI model is an empirical and data based model to predict the ionospheric variations [14]. The IRI model is being upgraded continuously when new data and new techniques are available. In 1978, the IRI model first version was released, and later this model was followed by several improved versions in 1986, 1990, and 1995, 2001, 2012, and 2016 [15–18]. The current version of this model is IRI-2016, which was released in 2017 [19]. The IRI model strongly depends on existing database whose regions are not covered by database experience reduced reliability of the model. India is one such region and needs careful attention while using this model. All released versions of the IRI model to estimate the VTEC are limited up to the height of 2000 km only. However, the TEC refers to the sum of electron contents of the ionosphere and plasmasphere. To get a more accurate comparison of the TEC, it is necessary to consider the plasmaspheric part of TEC. To overcome this problem, the IRI-Plas model (IRI extended to the plasmasphere) has been proposed which can estimate the TEC variation up to a height of 20,200 km [20]. The recent version of the model is IRI Plas 2017 [21]. The studies [22, 23] also showed that the IRI-Plas model overestimated the VTEC values obtained from GNSS receivers during the daytime hours. According to [24], the inaccurate estimation of the plasmaspheric TEC could be one of the reasons for the overestimation of TEC by the IRI-Plas model. [25], employing the IRI-Plas 2017 model, also showed that the IRI-Plas overestimated the GNSS derived TEC values mostly during the local daytime hours over all longitude sectors including the Asian sector. This overestimation can be resolved by using TEC assimilation techniques [26, 27]. By assimilating GIM TEC into the IRI Plas model, the electron density profile can be reconstructed in the scaled values of TEC, peak electron density (NmF2), and the peak height of the F2 layer (hmF2) [28]. The few investigations show a perfect agreement between assimilation of TEC output and observed TEC with good correlation coefficients and minimal percentage deviation after the ingestion of TEC into the model [29, 30].

This paper discusses the performance of global ionospheric models such as IRI 2016, IRI Plas 2017 with and without TEC assimilation, and GIM with Indian regional NavIC data instead of GPS over low latitude Indian region during the year 2017. The IRI models are coefficient less based models and in the absence of navigation data, and these models will help to predict direct VTEC for single frequency navigation receivers. Therefore, the performance evaluation of these models with NavIC data is necessary for Indian region. Thus, this paper discusses the validation of NavIC data with GPS and GLONASS data during 2017 year over IGS Hyderabad station, monthly and seasonal variation of VTEC due to NavIC data and global ionospheric models, and performance of the models with NavIC data during geomagnetic storm condition for different locations.

2. METHODOLOGY

The necessary experimental NavIC data to calculate Vertical Total Electron Content (VTEC) are obtained from IGS (IRNSS/GPS/SBAS (Satellite Based Augmentation System)) receiver installed at Hyderabad station (Lat: 17.39° N; Lon: 78.31° E). Initially, Slant Total Electron Content (STEC) calculated from the pseudo ranges measured in two different frequencies ($L5$ and $S1$) due to NavIC signals using Equation (1). STEC is the total number of electrons presented in the ionosphere along the signal path from the satellite to the receiver. It is measured in TEC unit ($1\text{TECU} = 10^{16}\,\text{el/m}^2$) [31]. The STEC depends on the length of the signal path through the ionosphere and is also dependent on the satellite elevation. To avoid this effect, an estimation of the VTEC above a given point on the Earth surface is necessary. To determine VTEC, the single thin layer model is used. By applying a suitable mapping function or slant factor, the elevation dependence is eliminated, and the resultant VTEC is obtained using Equation (2) [32].

$$\text{STEC} = \frac{1}{40.3}\left(\frac{f_1^2 f_2^2}{f_2^2 - f_1^2}\right)(P_2 - P_1) \tag{1}$$

where $f_1 = L5\,\text{signal} = 1176.45\,\text{MHz}$; $f_2 = S1\,\text{signal} = 2492.028\,\text{MHz}$; P_1, and P_2 are Pseudo range observables of $L5$ and $S1$ signals respectively in meters.

$$\text{VTEC} = \left[\sqrt{1 - \left(\frac{R_E * \text{Cos}\,E}{R_E + h_S}\right)^2}\,\right] * \text{STEC} \tag{2}$$

Here, 'STEC' is the slant TEC from satellite to the user, 'f' the carrier frequency of either $L5$ or $S1$ signals, 'R_E' the earth radius in kilometres, 'h_S' the altitude of IPP (Ionospheric Pierce Point) which is assumed to be 350 km, and 'E' the elevation angle of the satellite at the receiver location.

In order to evaluate the performance of the IRI 2016 model (https://ccmc.gsfc.nasa.gov/modelweb/-models/iri2016_vitmo.php), IRI extended to the plasmasphere (IRI-Plas2017) (http://ftp.izmiran.ru/pu-b/izmiran/SPIM/) and assimilation option of the IRI-Plas models in the estimations of the VTEC at Hyderabad station with NavIC-TEC, the monthly mean values of the TEC are calculated from the diurnal values of 5 most quiet and 5 most disturbed days of each month during the year 2017. Similarly, to investigate the seasonal VTEC variations while validating the models, the diurnal mean hourly VTEC values are averaged over each season. The seasons are taken as September equinox (August, September and October), December solstice (November, December and January), March equinox (February, March and April), and June solstice (May, June and July). The experimental NavIC-TEC values are also compared with GIM-TEC to evaluate discrepancies from the observed NavIC-TEC over the low latitude Indian region. Injecting TEC into IRI Plas model, convoluted with rescaling and optimization would significantly improve the performance of models. In this work, the TEC is also assimilated into the Plas model as an input to evaluate the model response to external input over the low latitude Indian region. The corresponding results are also compared with NavIC TEC. In this investigation, GIM TEC has been used to assimilate the model, which is available on the IONOLAB interface. According to [33], there are a number of sources for external TEC input that can be used in assimilation of the model. To better evaluate the VTEC prediction performance of the models, root-mean-square error deviations between the NavIC-VTEC and modelled VTEC have been computed using Equation (3). Similarly, the percentage of deviation (Error) between each of the experimental monthly and seasonal hourly mean VTEC values and the corresponding modelled VTEC values has been analysed. The computation has been done by subtracting the NavIC VTEC values from the corresponding IRI 2016 and IRI-Plas 2017 VTEC values as given in Equation (4).

$$\epsilon = \sqrt{(1/N)\sum_1^N \left(\text{VTEC}_{\text{observed or NavIC}} - \text{VTEC}_{\text{modeled}}\right)^2} \tag{3}$$

where 'N' represents the number of samples

$$\text{Percentage of deviation (Error)} = \frac{\text{VTEC}_{\text{modeled}} - \text{VTEC}_{\text{observed or NavIC}}}{\text{VTEC}_{\text{observed or NavIC}}} \times 100 \tag{4}$$

The percentage of improvement in the prediction of RMSE values between the models is calculated for quiet days and disturbed days for each month and season during 2017 year using the following equations.

$$\text{Difference 1} = \frac{\epsilon_1 - \epsilon_0}{\epsilon_1} \times 100 \tag{5a}$$

$$\text{Difference 2} = \frac{\epsilon_2 - \epsilon_0}{\epsilon_2} \times 100 \tag{5b}$$

$$\text{Difference 3} = \frac{\epsilon_2 - \epsilon_1}{\epsilon_2} \times 100 \tag{5c}$$

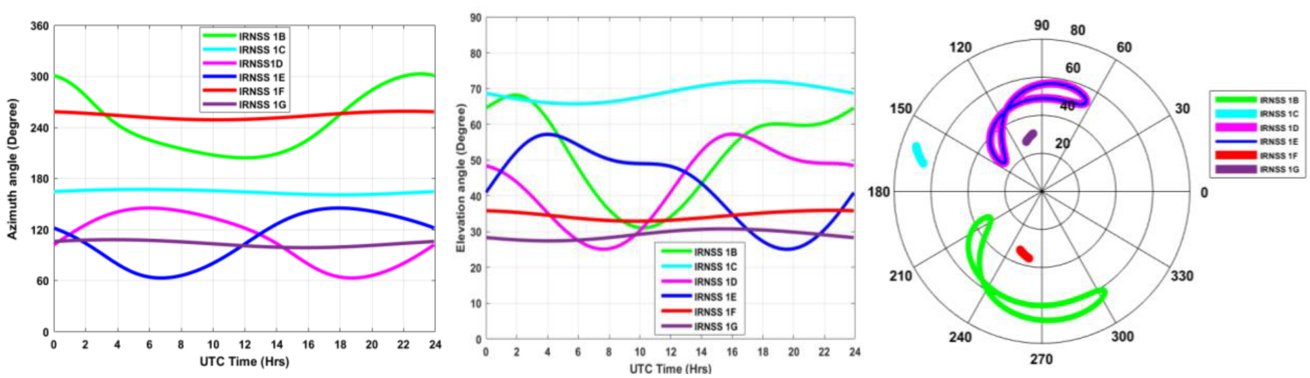
where ϵ_1, ϵ_2, and ϵ_0 are the RMSE values of the IRI Plas model, IRI 2016 model, and IRI Plas with TEC input mode with respect to NavIC TEC.

3. RESULTS AND DISCUSSION

The results section in this paper deals with the validation of NavIC data with GPS and GLONASS, and performance evaluation of the global ionospheric models with NavIC data for all months and seasons during the year 2017 for quiet and disturbed days over a low latitude Hyderabad station. Also, the performance of the global ionospheric models is discussed for a storm time during the year 2017 for different stations.

3.1. Performance Evaluation of NavIC System

The visibility of IRNSS satellites over the Indian geographical region is observed. Figure 1(a)–(c) show the variation of elevation, azimuthal angle, and skyplot of IRNSS satellites on the 8th September, 2017. When using any navigation system, it is important to know how many satellites are tracking and their position in the sky. The satellite sky plot's visual and graphical screen assists in pinpointing when satellites are covered by surrounding structures, trees, and mountains. Usually four satellites are required to determine position. Satellite skyplot can be a helpful tool to monitor the current satellite configuration. From Figure 1, it is observed that all available satellites in IRNSS constellation are visible over a period of 24 hours. IRNSS 1C, 1F, 1G satellites appear in geostationary orbit, and IRNSS IB, 1E, 1D satellites are in geosynchronous orbit. There is no visibility gap observed. All IRNSS satellites are continuously visible to user in a day without any interruption in the NavIC service to the user. Recently, a few authors evaluated the performance of NavIC system. The results presented that the NavIC system performed well and provided good signals for accurate user position determination and ionospheric studies. Hence, NavIC system can be used as a good navigational system for the Indian region [34–36].



(a) (b) (c)

Figure 1. Variation of (a) azimuth, (b) elevation angles, (c) sky plot of IRNSS satellites at Hyderabad station with respect to UTC time on 8th September, 2017.

Figure 2(a)–(b) show the variation of VTEC due to IRNSS, GPS, and GLONASS with respect to UTC time for quiet and disturbed days over Hyderabad station. In order to validate the performance of NavIC system, ionospheric TEC due to NavIC signals is compared with the GPS and GLONASS TEC for quiet and disturbed conditions. The GPS and GLONASS TEC are collected from IONOLAB, IGS network at Hyderabad station (www.ionolab.org). From the results it is found that there is a good correlation between NavIC-GPS and NavIC-GLONASS TEC. The average TEC calculated from IRNSS satellites closely follows the GPS and GLONASS TEC, and the corresponding correlation coefficients are presented in Table 1, for quiet and disturbed days, respectively. Therefore in this paper, the NavIC data are used to validate the global ionospheric models over low latitude Indian region.

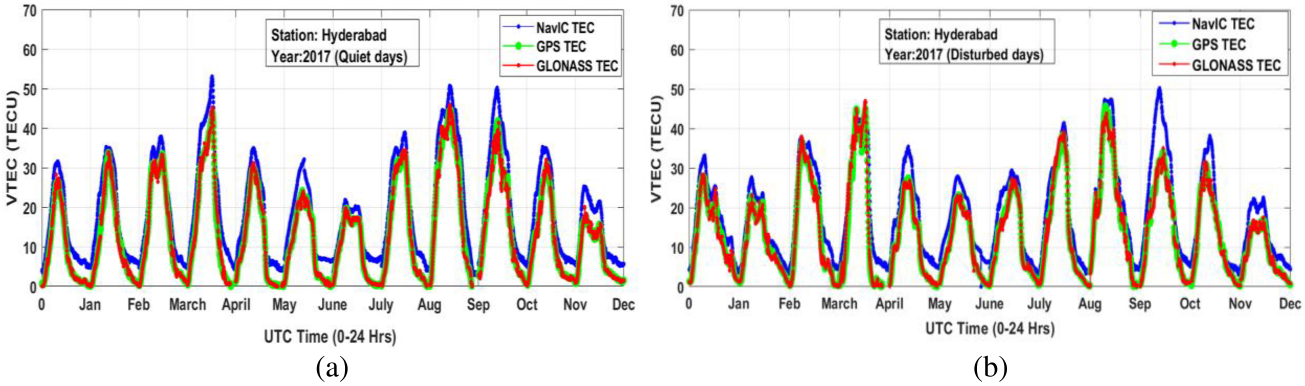


Figure 2. Variation of VTEC due to NavIC, GPS and GLONASS for (a) quiet days, (b) disturbed days during the year 2017 over low latitude Hyderabad station.

Table 1. Correlation between NavIC-GPS TEC and NavIC-GLONASS TEC for quiet and disturbed days during the year 2017 over low latitude Hyderabad station.

Month	Correlation between NavIC-GPS Quiet day/Disturbed day	Correlation between NavIC-GLONASS Quiet day/Disturbed day
Jan	0.995/0.991	0.994/0.984
Feb	0.923/0.990	0.914/0.984
March	0.994/0.993	0.994/0.986
April	0.994/0.954	0.995/0.952
May	0.996/0.997	0.995/0.996
June	0.972/0.990	0.973/0.985
July	0.989/0.986	0.990/0.975
Aug	0.976/0.988	0.982/0.983
Sep	0.987/0.988	0.981/0.987
Oct	0.994/0.976	0.990/0.972
Nov	0.982/0.958	0.975/0.963
Dec	0.996/0.989	0.992/0.988

3.2. Diurnal Monthly and Seasonal Variation of VTEC and Models Comparison

Figures 3–10 show the monthly and seasonal variations of VTEC and percentage of error deviation between models and NavIC data for quiet and disturbed days during the year 2017 over low latitude Hyderabad station. A gradual increase is observed in TEC from 00:00 UT to 09:00 UT, a peak value around 09:00 UT and a gradual decrease from 09:00 UT to 16:00 UT, minimum values with slight variations from 16:00 UT 23:00 UT for both quiet and disturbed days due to models and observed NavIC data. The difference between the universal time (UT) and local time (LT) is about 5 hr, 30 min. The GIM-TEC follows the NavIC TEC pattern with slight difference over a period of 24 hr. The IRI 2016 model overestimates during 04:00 UT to 12:00 UT, underestimates between 12:00 UT and 23:00 UT, and closely following from 00: 00 UT to 04:00 UT, while IRI Plas model overestimates between 00:00 UT and 12:00 UT and following the NavIC TEC with slight variation during the rest of the time. The TEC due to IRI Plas model is much greater than NavIC TEC which is in good agreement with reports over other stations using GPS data [37, 38]. It can be said that empirical models underestimate the TEC values at night time and overestimate during the day time. Moreover, the IRI 2016 and IRI Plas

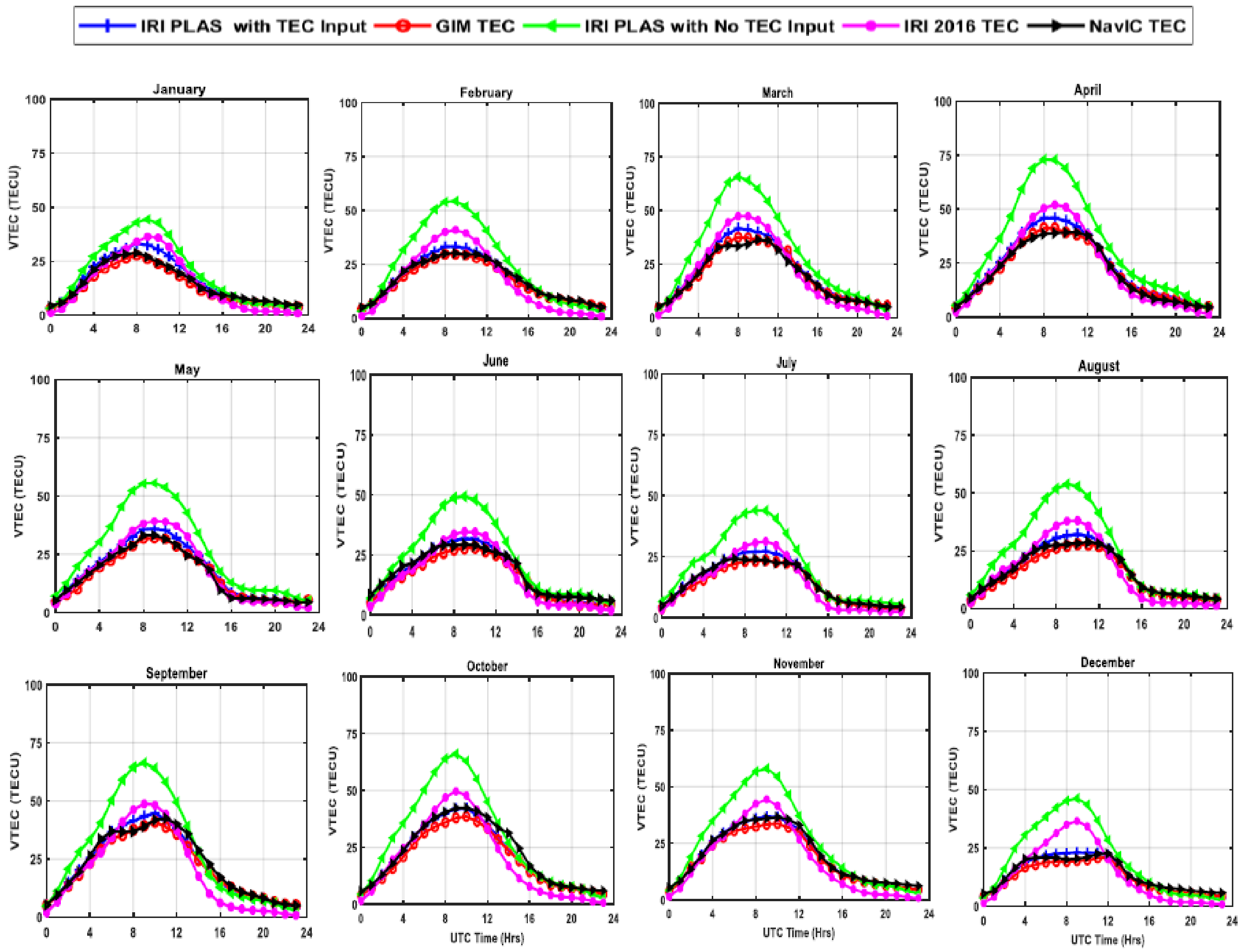


Figure 3. Monthly mean of diurnal variation of VTEC due to IRI-Plas 2017 with TEC input, GIM, IRI-Plas with no input, IRI-2016 and NavIC data for geomagnetic quiet days during the year 2017.

2017 models are unable to predict the difference between quiet and disturbed days, unlike the observed NavIC and GIM TEC. However, when the IRI Plas model is assimilated with external TEC input, we find good agreement between model TEC and NavIC TEC with least percentage of error deviations and RMSE values for both quiet and disturbed days. For quiet days, the monthly highest and lowest peak observed VTEC values due to NavIC data are about 42.53 and 22.52 TECU which are observed in September and December, respectively. Similarly, the highest (52.06 TECU) and lowest (31.28 TECU) peak VTEC values are observed in April and July respectively with IRI 2016 model; 72.94 (highest) and 44.02 (lowest) VTEC values are observed in April and July respectively with IRI Plas 2017 model; 41.15 (highest) and 20.86 (lowest) VTEC values are observed in April and December respectively with GIM model; 45.87 (highest) and 22.95 TECU lowest) VTEC values are observed in April and December respectively with assimilation of TEC into IRI Plas model. For disturbed days, the monthly highest and lowest peak observed VTEC values due to NavIC data are about 48.35 and 24.71 TECU which are observed in April and July, respectively. Similarly, the highest (55.50 TECU) and lowest (31.26 TECU) peak VTEC values are observed in October and July respectively with IRI 2016 model; 73.49 (highest) and 43.61 (lowest) VTEC values are observed in October and July respectively with IRI Plas 2017 model; 47.25 (highest) and 24.10 (lowest) VTEC values are observed in September and December respectively with GIM model; 50.50 (highest) and 26.93 (lowest) VTEC values are observed in April and December respectively with assimilation of TEC into IRI Plas mode. From above analysis it is

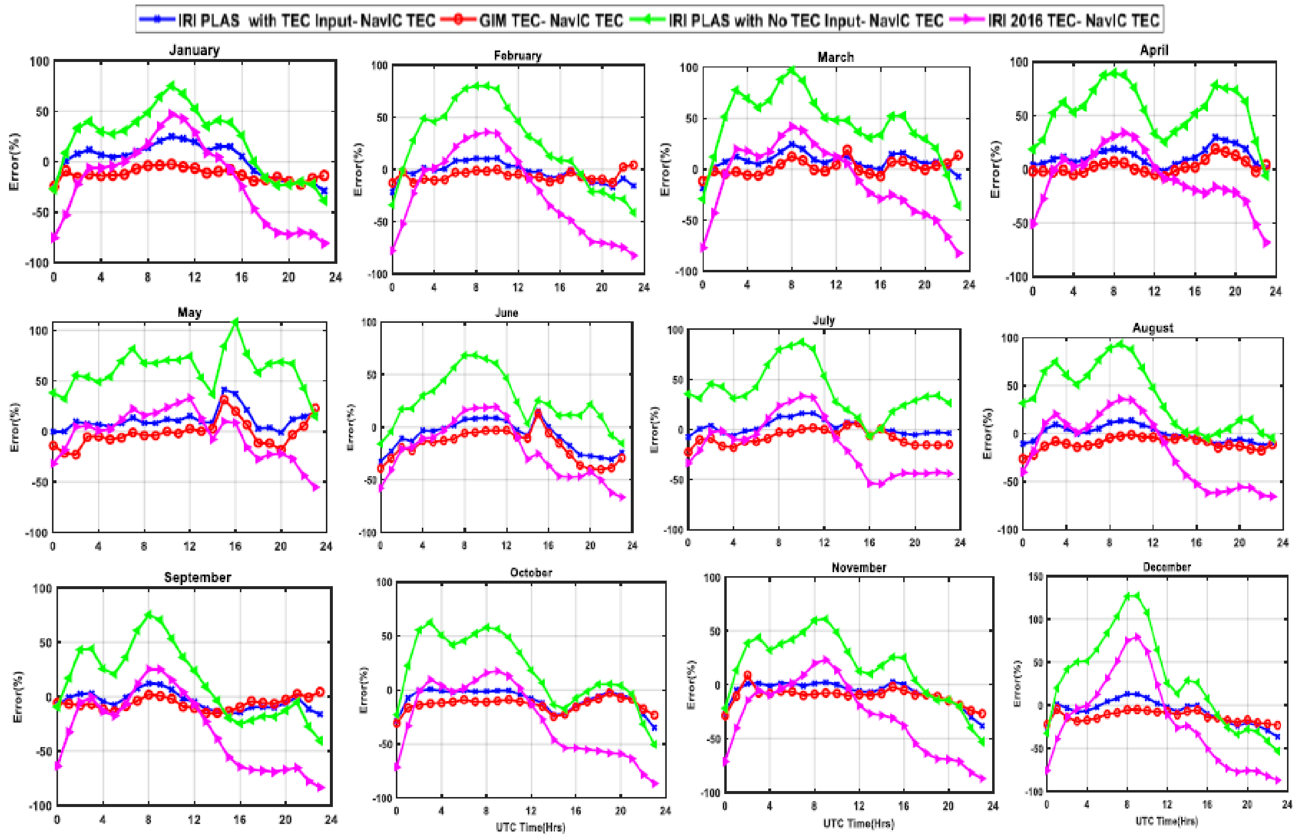


Figure 4. Error percentages of estimated VTEC by standard models (IRI Plas with TEC input, GIM, IRI Plas with no TEC input and IRI-2016) from NavIC TEC for geomagnetic quiet days during the year 2017.

observed that the highest and lowest peak modeled VTEC values due to IRI 2016 and IRI Plas 2017 are more or less same for quiet and disturbed days, whereas IRI Plas with TEC input, GIM and NavIC show significant difference between their peak values. The maximum and minimum peak values of VTEC for both the observed and modeled are observed in the equinox months and solstice months, respectively. In addition, the seasonal highest and lowest peak observed and modeled VTEC values are observed in the March equinox and June solstice respectively for both quiet and disturbed days. Based on studies, the maximum and minimum seasonal effects are at equinoctial and June solstice, respectively [39, 40], which agree by the results of this paper. From Figures 4, 6, 8, and 10 it can be said that when the deviation (Error %) is positive, the model overestimates the observed TEC values, and when the deviation is negative, the model underestimates the observed TEC values. Moreover, the IRI Plas 2017 version shows the overestimation of VTEC as compared to others (IRI 2016, IRI Plas 2017 with TEC input and GIM) during low solar activity period. For instance, on quiet days, the highest monthly and seasonal error deviations about 130% and 89.07% are observed between the modeled and corresponding observed values in December and the March equinox respectively when IRI Plas 2017 version is used, and similarly, for disturbed days about 100% and 77.24% are observed in December and June solstice. This discrepancy is not due to the plasmaspheric TEC, rather the problem could be due to the poor representation of top side IRI ionosphere. When IRI Plas model is assimilated with GIM TEC, the resultant TEC is closer to the NavIC data, and percentage of error is around less than ±15% only compared to other models, which show large deviations.

The monthly and seasonal arithmetic means and RMSEs of observed and modeled VTEC variations (NavIC, IRI Plas 2017 with TEC input, GIM, IRI Plas and IRI 2016 models) over Hyderabad station during 2017 year for quiet and disturbed days are shown in Figures 11–14. For instance, the highest

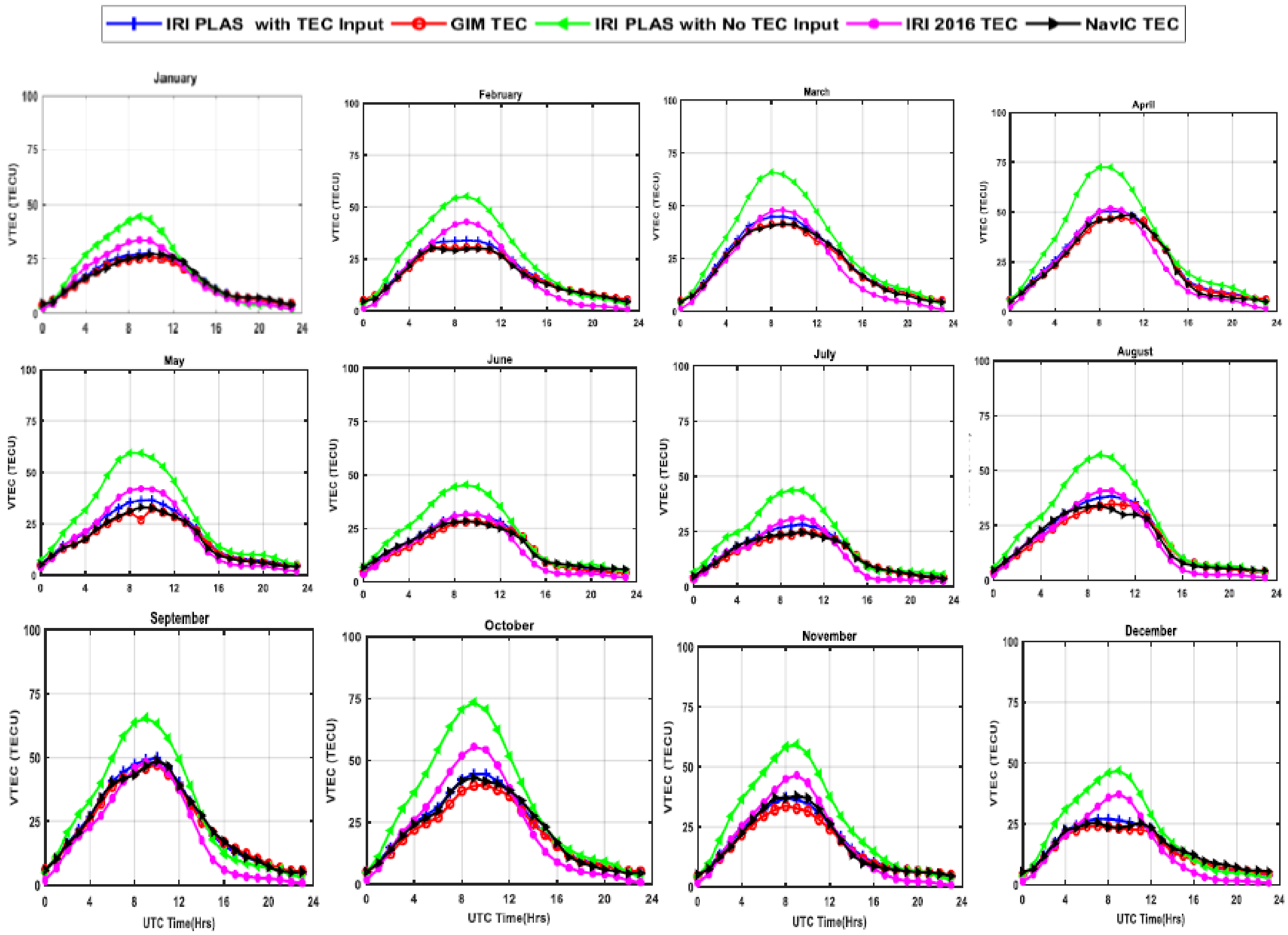


Figure 5. Monthly mean of diurnal variation of VTEC due to IRI-Plas 2017 with TEC input, GIM, RI-Plas with no input, IRI-2016 and NavIC data for geomagnetic disturbed days during the year 2017.

monthly mean VTEC values of NavIC, GIM, IRI 2016, IRI Plas 2017, and IRI Plas with TECinput for quiet day are about 22.69 (September), 21.04 (September), 22.07 (April), 33.20 (April), and 22.99 TECU (April), respectively, and lowest monthly mean VTEC values are about 13.65 (December), 12.09 (December), 13.88 (December), 19.90 (January), and 13.29 TECU (December), respectively. Similarly, the highest monthly mean VTEC values for disturbed days are about 23.93 (September), 23.84 (September), 22.27 (April), 33.21 (April), and 25.33 TECU (April), respectively, and the lowest monthly mean VTEC values are about 14.35 (July), 14.00 (July), 13.93 (July), 19.45 (January), and 15.02 TECU (December), respectively. In addition, the maximum and minimum seasonal mean observed VTEC values are obtained in September equinox and June solstice, and modeled VTEC values are predicted in March equinox and December solstice, respectively. The IRI Plas 2017 with TEC input option gives relatively lower RMSE values than other models (IRI 2016 and IRI Plas 2017).

For example, in April the RMSE values due to IRI 2016, IRI Plas 2017, GIM, and IRI Plas with TEC input option are 5.36, 16.49, 1.19, and 3.15 TECU respectively for quiet days. Moreover, IRI 2016 and IRI Plas 2017 models do not respond to disturbed days unlike NavIC and GIM. Due to this the RMSE values are more or less equal for quiet and disturbed days.

To evaluate the performance of the models, the monthly and seasonal percentages of deviation of RMSE values (Difference 1, Difference 2, and Difference 3) are also computed and shown in Figures 15–16 for quiet and disturbed days. Difference 1 and Difference 2 indicate the percentages of improvement of IRI Plas 2017 with TEC assimilation over IRI Plas 2107 with no extra TEC input and IRI 2016 model respectively. Similarly, Difference 3 indicates the percentage of improvement of IRI 2016 model over IRI

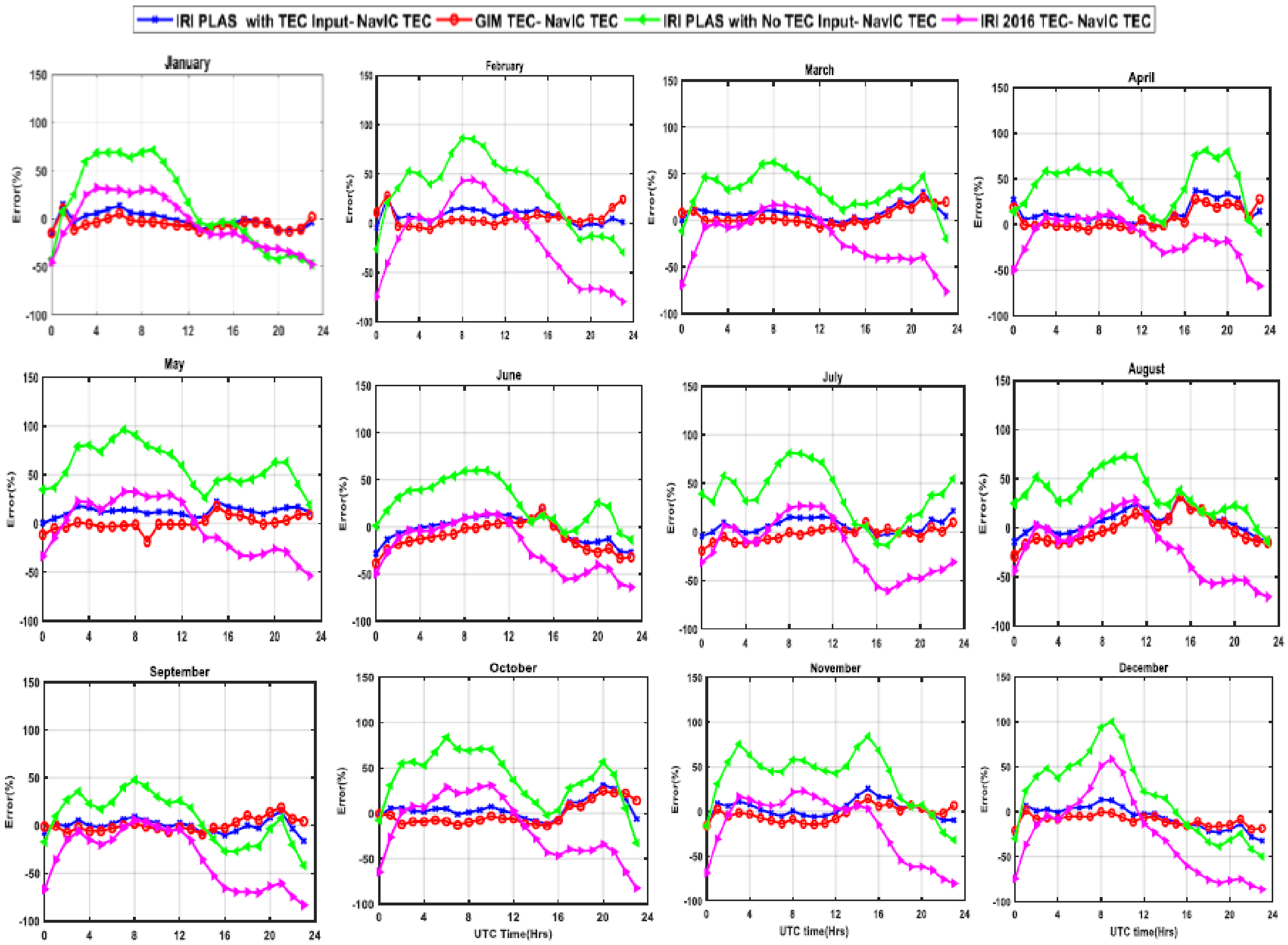


Figure 6. Error percentages of estimated VTEC by standard models (IRI Plas with TEC input, GIM, IRI Plas with no TEC input and IRI-2016) from NavIC TEC for geomagnetic disturbed days during the year 2017.

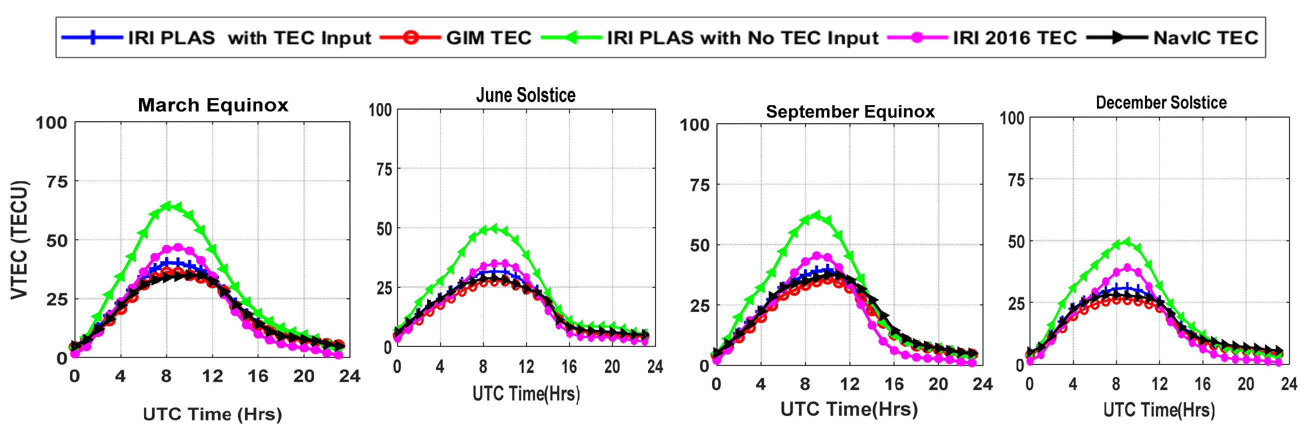


Figure 7. Seasonal mean variation of VTEC due to IRI-Plas 2017 with TEC input, GIM, IRI-Plas with no input, IRI-2016 and NavIC data for geomagnetic quiet days during the year 2017.

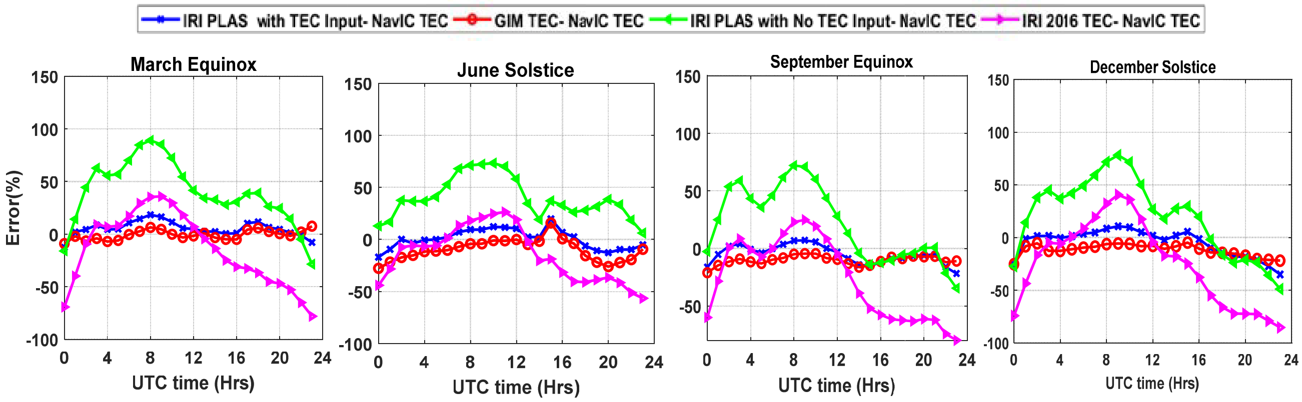


Figure 8. Seasonal variation of error percentages of estimated VTEC by standard models from NavIC TEC for geomagnetic quiet days during the year 2017.

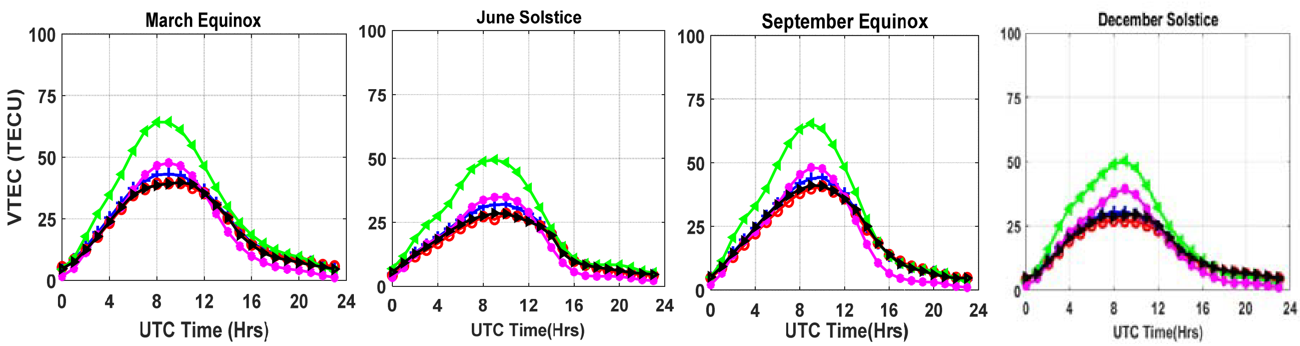


Figure 9. Seasonal mean variation of VTEC due to IRI-Plas 2017 with TEC input, GIM, IRI-Plas with no input, IRI-2016 and NavIC data for geomagnetic disturbed days during the year 2017.

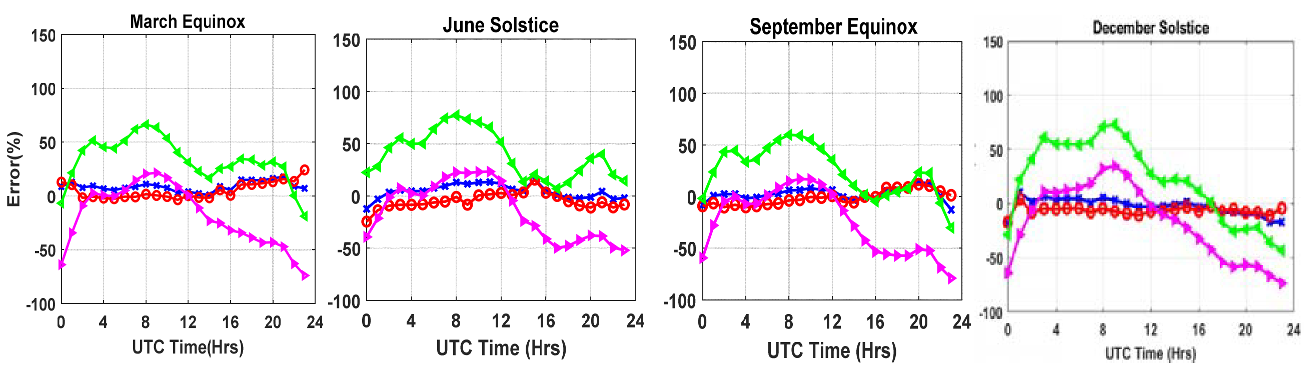


Figure 10. Seasonal variation of error percentages of estimated VTEC by standard models from NavIC TEC for geomagnetic disturbed days during the year 2017.

Plas 2017 without TEC assimilation of the model. For instant, the highest % of Difference 1, Difference 2, and Difference 3 are 88.72% (November), 79.54% (December), and 70.51% (May), respectively for quiet days, similarly for disturbed days 90.57% (October), 77.89% (October), and 70.48% (April), respectively. In addition, for seasons the highest % of Difference 1, Difference 2, and Difference 3 are 86.26% (September equinox), 73.48% (December solstice), and 67.25% (June solstice) respectively for quiet days, similarly for disturbed days 89.90% (September equinox), 77.10% (December solstice), and

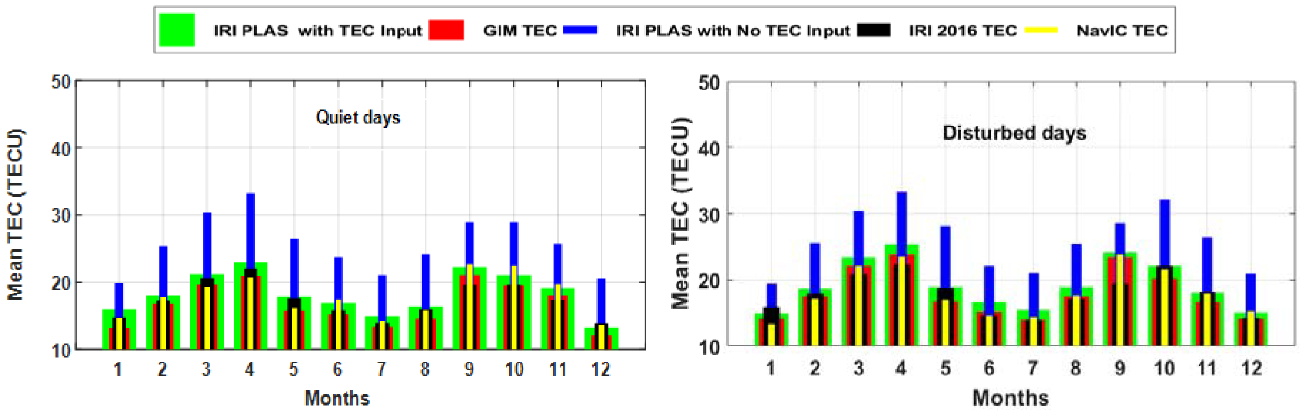


Figure 11. Monthly arithmetic means of diurnal hourly VTEC variation and validation of the IRI Plas with input, IRI Plas and IRI 2016 models over Hyderabad station during 2017 year.

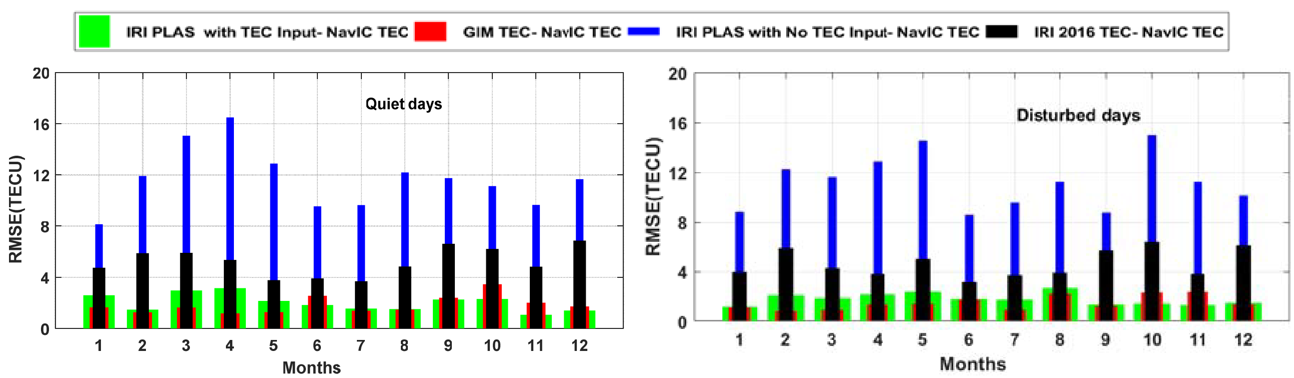


Figure 12. Monthly RMSE variation and validation of the IRI Plas with input, GIM, IRI Plas and IRI 2016 models over Hyderabad station during 2017 year.

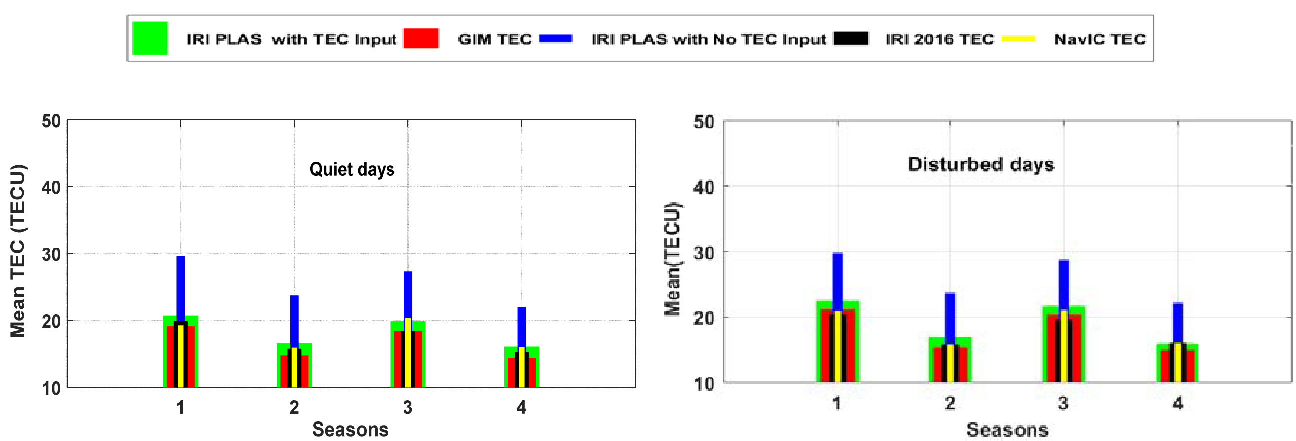


Figure 13. Seasonal arithmetic means of diurnal hourly VTEC variation and validation of the IRI Plas with input, GIM, IRI Plas and IRI 2016 models over Hyderabad station during 2017 year.

66.08% (June solstice), respectively. From this study, it is found that the IRI 2016 model follows NavIC TEC better than IRI Plas 2017, and IRI Plas with TEC input mode performs better than IRI 2016. Only slight variations are observed between NavIC and GIM TEC. The IRI Plas model with GIM TEC assimilation performs more or less the same as GIM with respect to NavIC data.

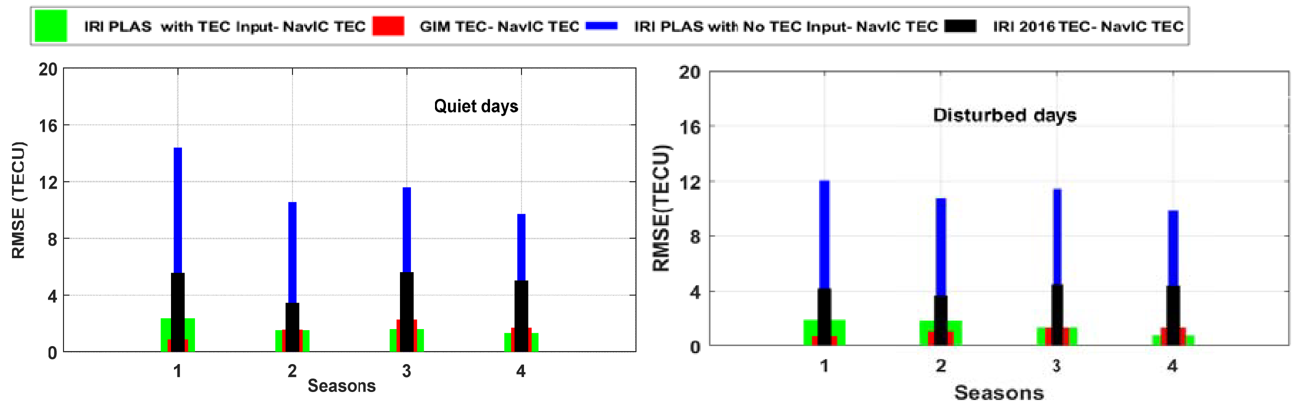


Figure 14. Seasonal RMSE variation and validation of the IRI Plas with input, GIM, IRI Plas and IRI 2016 models over Hyderabad station during 2017 year for quiet and disturbed days.

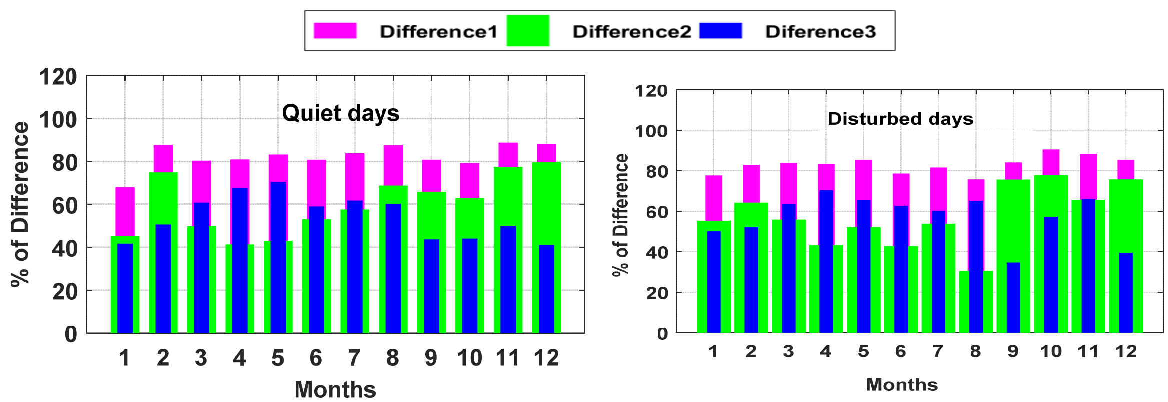


Figure 15. Monthly percentage differences of RMSE values of the IRI Plas with input, IRI Plas and IRI 2016 models over Hyderabad station during 2017 year for quiet and disturbed days.

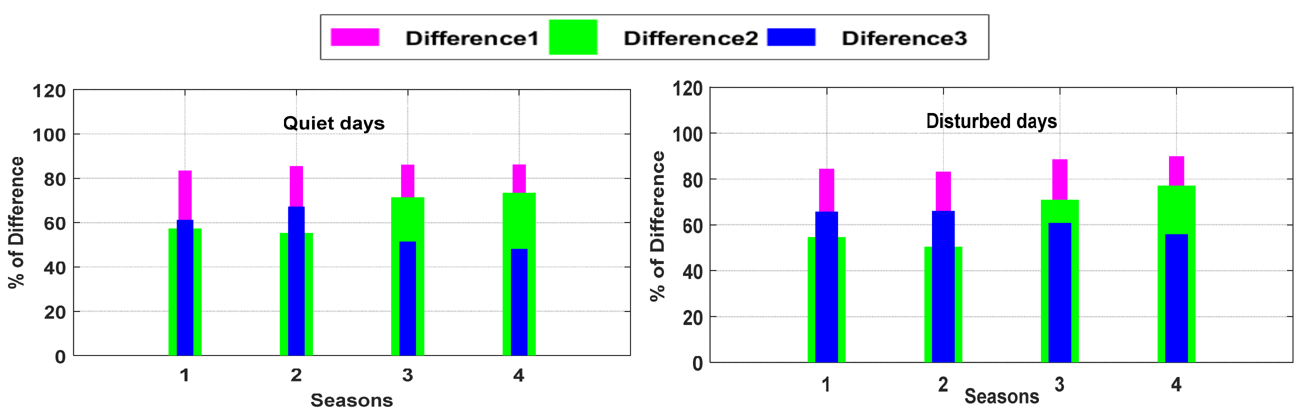


Figure 16. Seasonal percentage difference of RMSE values of the IRI Plas with input, IRI Plas and IRI 2016 models over Hyderabad station during 2017 year for quiet and disturbed days.

3.3. Performance of the Models with NavIC Data during Geomagnetic Storm Condition

This work also focuses on the performance of models at five different locations such as Hyderabad (Lat: 17.39° N, Lon: 78.31° E), Kurnool (Lat: 15.79° N, Lon: 78.07° E), Guntur (Lat: 16.44° N, Lon: 80.62° E), Surat (Lat: 21.16° N, Lon: 72.78° E), and Indore (Lat: 22.52° N, Lon: 75.92° E)

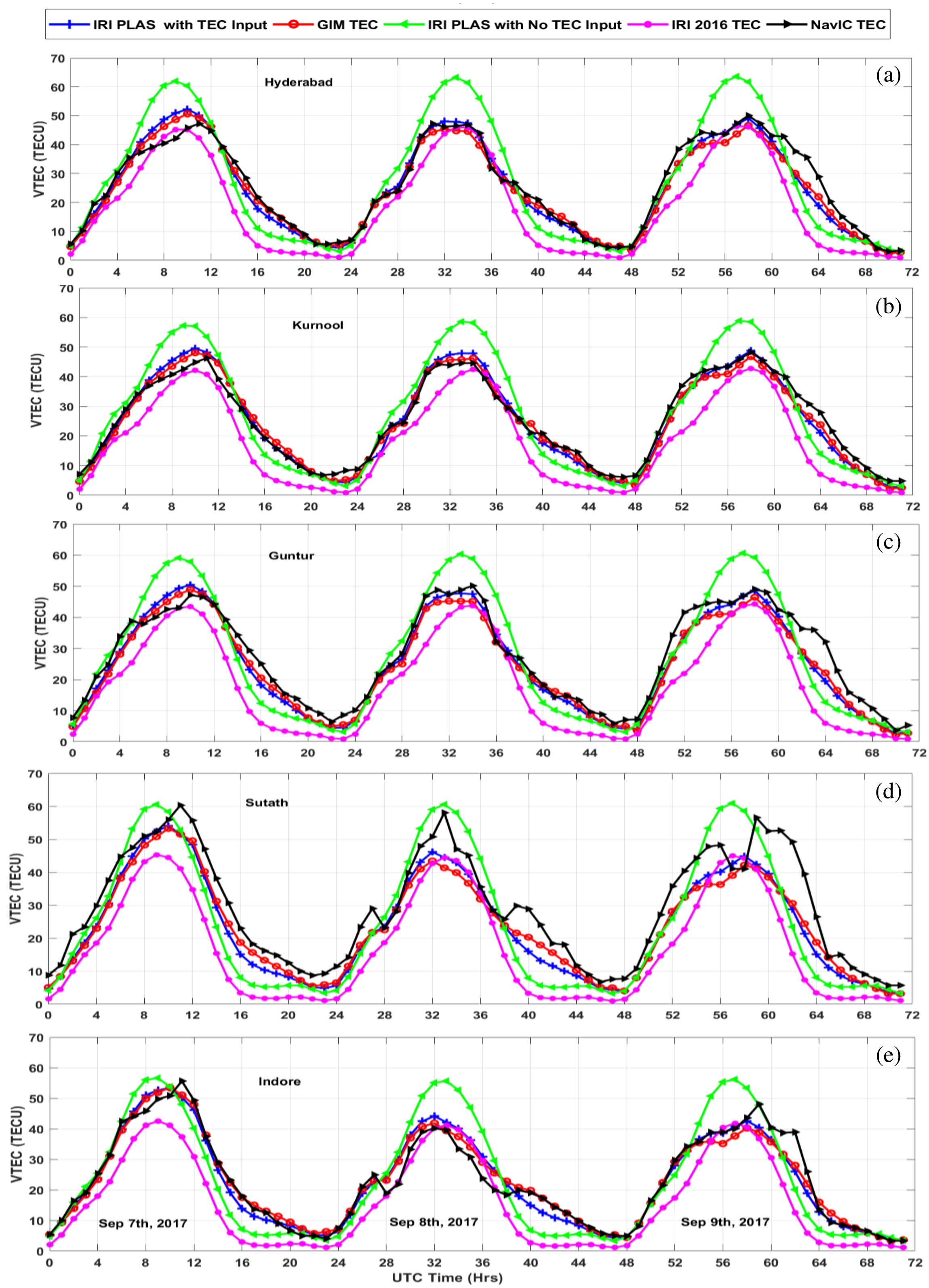


Figure 17. Variation of VTEC due to models and NavIC on geomagnetic strom during September 7th to 9th, 2017 over (a) Hyderabad, (b) Kurnool, (c) Gunture, (d) Surath, (e) Indore stations.

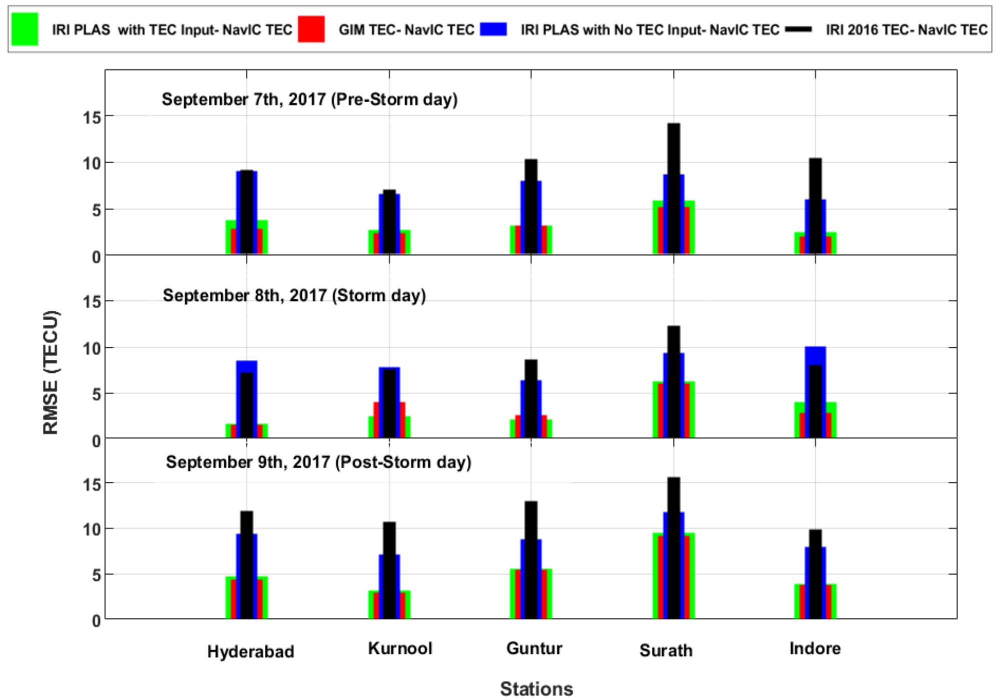


Figure 18. RMSE variations by standard models (IRI Plas with TEC input, GIM, IRI Plas with no TEC input and IRI-2016) from NavIC TEC for geomagnetic storm during the year 2017, September for different stations.

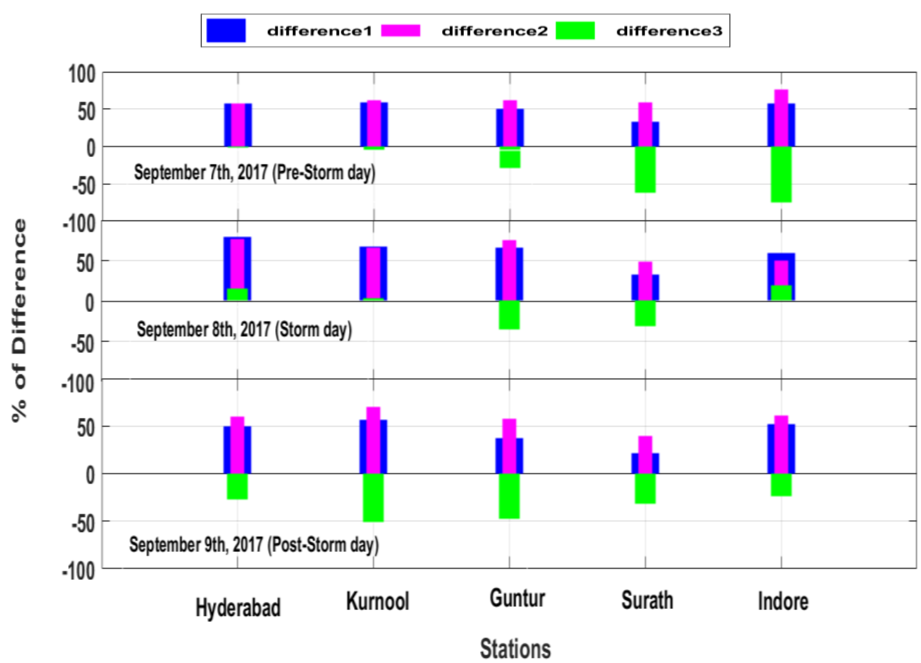


Figure 19. Percentage difference of RMSE values of the IRI Plas with input, IRI Plas and IRI 2016 models for geomagnetic storm during the year 2017, September for different stations.

during the geomagnetic storm condition over the Indian region. The predicted TEC due to the models is compared with NavIC TEC. The analysis is carried out for the 7th, 8th, and 9th September, 2017 (Pre storm, Storm, and Post storm days). These days are selected based on the Dst and Kp indices (http://wdc.kugi.kyoto-u.ac.jp/kp/index.html). The average values of Kp and Dst of pre-storm, storm, and post-storm days are 3.7, 6, 0.7 and −10, −107, −65, respectively. The Dst and Kp values indicate the disturbance level of ionosphere. Variation of VTEC due to models and NavIC on geomagnetic strom during September 7th to 9th, 2017 over Hyderabad, Kurnool, Gunture, Surath, and Indore stations is shown in Figure 17. The NavIC VTEC values show significant variation that specifies the occurrence of storm. On the other hand, the VTEC values due to models (IRI 2016, IRI 2017) do not show any change when the storm option of the models is "on". It is observed that the modeled VTEC values during three days of geomagnetic storm follow almost the same pattern. However, when IRI Plas model is assimilated with TEC input, the improvement in the model performance is observed with the lowest RMSE values and better percentage improvements than others. Figure 18 shows the RMSE variation by IRI Plas with TEC input, GIM, IRI Plas with no TEC input, and IRI-2016 from NavIC TEC for geomagnetic storm during the year 2017, September for different stations. It is observed that the RMSE values of IRI 2016 model are higher than IRI Plas 2017 over Guntur and Surath stations during three days of storm time and same effect observed during post storm day over 5 stations. The Percentage difference of RMSE values of the IRI Plas with input, IRI Plas, and IRI 2016 models with respect to NavIC data for pre-storm, storm, and post storm days in the month of September during year 2017 for different stations are shown in Figure 19. The negative percentage of Difference 3 indicates that IRI Plas performs better than IRI 2016 model. Difference 1 and Difference 2 are the same during the first two days of storm over Hyderabad and Kurnool stations. It means that the percentage of performance improvement of IRI Plas model with TEC assimilation is the same as the IRI 2016 and IRI Plas 2017 models. These results will be helpful in future enhancement of the model updates.

4. CONCLUSIONS

This work focuses on the ionospheric TEC variability over low latitude Indian region with NavIC based observations. The major contributions in this work are the comparative analysis of regional NavIC derived TEC with GIM TEC and widely used global empirical model IRI-2016, its extension to the plasmasphere, i.e., IRI- Plas 2017 model with extra TEC input apply to diurnal, seasonal and storm time variations over the Indian low latitude Hyderabad station. The NavIC TEC compared with the models and RMSE values and % of error are calculated for each month by considering five quiet and five disturbed days and seasons during year 2017 over Hyderabad station. The RMSE values, percentage of errors, and model performance improvements of IRI 2016 model are better than IRI Plas model. However, the plasmaspheric part of TEC is not contributed.

The IRI Plas model predicts electron contents of the ionosphere and plasmasphere. In this study, the IRI Plas model shows an overestimated TEC compared to the NavIC TEC irrespective of days and seasons, and its performance is poor during daytime over low latitude region. It could be due to the poor representation of plasmaspheric TEC of the model. Further improvements are necessary to the model. Otherwise, to obtain better performance of the model data assimilation is necessary over low latitude regions. In this work, it is found that when the model is assimilated to extra TEC input, the prediction of TEC is significantly improved for quiet and disturbed days compared to others. This work also suggests that the assimilation of TEC input into the model is effective to predict the storm time TEC estimation.

The performance of the models is also tested for strong geomagnetic storm condition during September 7–9, 2017 with NavIC data for 5 different locations. IRI Plas 2017 performs better than IRI 2016 model on post storm day for 5 locations. The highest RMSE values are found on post storm day in all models for 5 locations. The improvement in the IRI Plas model with assimilation performance is observed with the lowest RMSE values and better percentage improvements than others.

The faithful estimation of TEC will be useful in satellite navigation applications. The results show that not only GPS data but also NavIC data can be used to evaluate the performance of global models. The results and analysis presented in this paper will be very helpful in the development of regional error correction values using respective satellite navigation constellations data. For more conclusions, the proposed study can be extended to large amount of data for a number of stations for different solar activities.

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