Comparison and Validation of VTEC Derived from GPS, IRI-Plas and NeQuick-2 During 2015 and 2019 in India

Alluri, V.,[1] Chowdhary. V. R.,[1] Joshi, S.,[1,2] Banerjee, S.[3] and Kothari, N.[1]
[1]Department of Electronics and Telecommunication, International Institute of Information Technology Pune, India
[2]Department of Computer Science, Savitribai Phule Pune University, Pune, India
[3]Department of Computer Engineering, International Institute of Information Technology, Pune, India

Abstract
The paper compares Vertical Total Electron Content (VTEC) values extracted from IGS's distributed network of dual-frequency GPS stations in India, and the VTEC values extracted through IRI-Plas-2017 and NeQuick-2.0.2 models at the same locations and the same durations of time. Diurnal variation and relative deviation of modelled and measured VTEC of IGS reference stations at Lucknow (LCK3, Latitude: 26.91218, Longitude: 80.95564) and Hyderabad (HYDE, Latitude: 17.41728, Longitude: 78.55088) are visualized through graphical representation, during 2015 and 2019. Further, statistical analysis was performed on both datasets. The outputs of this project revealed that, the magnitude of maximum relative deviation of modelled VTEC from measured VTEC was high while using IRI-Plas model at Lucknow and Hyderabad in each month of solar maximum and solar minimum. Furthermore, during solar minimum, VTEC is highly overestimated by both models during peak hours of ionization and the magnitude of overestimation at these hours is higher while using IRI-Plas model for both regions. Finally, the highest coefficient of determination value was recorded at Hyderabad during 2019 while using IRI-plas model. The R^2 analysis shows that IRI-Plas model produces a more accurate representation of VTEC during solar minimum and maximum at both regions.

1. Introduction

Total Electron Content (TEC) has been an important parameter to study disturbances in the ionosphere that are caused by variations in intensity of solar radiation. While comprehensive analysis on TEC derived from trans-ionospheric radar instruments started as early as 1957 (Evans, 1957 and Bauer and Daniels, 1959), with the advent of artificial satellites, TEC derived from Global Navigation Satellite Systems (GNSS) is currently the most preferred data source for observing ionospheric behaviour (Mendillo, 2005). Over the last 20 years, while several researchers offered successful insight on the diurnal, monthly, seasonal and annual variations in TEC at various latitudinal regions (Bhattacharya et al., 2009, Unnikrishnan et al., 2002 and D'ujanga et al., 2012), several others offered an insight into the electromagnetic phenomena responsible for short-term and long-term impacts of solar radiation on ionospheric TEC (Chauhan and Singh, 2010, Anderson et al., 2006 and Appleton, 1946).

Based on years of research on ionospheric plasma, a data-based empirical model named International Reference Ionosphere (IRI) was first launched in 1978, as a standard for ionospheric parameters. Over time, with the emergence of better modelling techniques and newer datasets, updated versions of IRI such as: IRI-1985, IRI-1990, IRI-2000, IRI-2007, IRI-2016 and most recently IRI-Plas, were launched (Bilitza, 1990, Bilitza et al., 2000 and Bilitza and Reinisch, 2008). TEC, is one amongst the thirty-seven other ionospheric parameters that are calculated by IRI. Similarly, NeQuick is another prominent ionospheric model that is developed by the International Centre for Theoretical Physics (ICTP) in Italy, along with the University of Graz in Austria. It is a three-dimensional and time-dependent empirical model of the ionosphere's electron density profile. Unlike the IRI-model, TEC and electron density are the only two parameters calculated by NeQuick. The latest version of this model is NeQuick-2.

In this study, Vertical Total Electron Content (VTEC) extracted from GPS, IRI-Plas and NeQuick-2 are compared at two regions in India during 2015 and 2019. The comparative and correlation analysis aims to quantify deviation of modelled TEC data from measured TEC data, at a mid-latitude region and a low-latitude region of India, during the solar maximum (2015) and solar minimum (2019).

Online ISSN 2673-0014/

2. Literature

2.1 Total Electron Content (TEC)

TEC is a parameter widely used to depict the effect of solar radiation on the ionosphere. TEC can be defined as the total number of electrons that are present in an area enclosed by a tube with an arbitrary cross-section of 1 square meter laid over the entire length between the satellite and receiver (Okoh et al., 2015). TEC values will be high during the daytime due to ionization by X-rays and UV-rays, and low during night-time due to the recombination process. Further, when Interplanetary Magnetic Fields (IMF) directed towards earth interact with the magnetosphere, electromagnetic processes govern TEC enhancements and depletions in the ionosphere. Also, TEC is directly proportional to signal delay because the increase in free electrons in the ionosphere creates a highly dispersive medium through which GPS signals must travel.

2.2 Solar Cycle

The intensity of solar activity increases and decreases in an 11-year cycle. This solar cycle dictates the extremity of X-rays and UV-rays emitted by the sun. Therefore, the solar cycle has dramatic implications on the electromagnetic mechanisms of the Earth's upper atmosphere (David, 2015). In a typical solar cycle, intensity of solar activity increases through the first five or six years until it reaches a maximum, and then decreases through the remainder of the 11-year cycle until it reaches a minimum. The current solar cycle i.e. solar cycle 24 is predicted to end in 2020. The cycle's solar maximum was reached in 2014-15.

2.3 International GNSS Service (IGS)

IGS provides highly precise navigation information through over 400 global permanent GNSS stations and close to 200 organizations spread over 100 countries are responsible for contributing towards the establishment of this organization (source: www.igs.org). The accuracy and precision of GNSS measurements is very high. GNSS data derived from the IGS network fundamentally measures two atmospheric parameters: The Tropospheric Zenith Path Delay (ZPD) and Ionospheric TEC. This is done by combining pseudo-range measurements of GNSS with IGS precise clocks and orbits (Kouba, 2009). IGS hosts data obtained predominantly from a single satellite navigation system i.e., Global Positioning System (GPS). More recently, data from Russia's GLObal NAvigation Satellite System (GLONASS) has been incorporated into the IGS workflow. The data is available for download from the IGS data portal, which is hosted by National Aeronautics and Space Administration (NASA). IGS station in Lucknow (LCK3) is located at 26.91218 N and 80.95564 E, and IGS station in Hyderabad (HYDE) is located at 17.41728 N and 78.55088 E.

2.4 TEC Derived from Dual-Frequency GPS

In a GNSS network such as the GPS, for the 'navigation message' to travel from the satellite to the receiver, a 'carrier wave' is required. In case of a dual-frequency GPS design, two carrier waves are used: L1 at 1575.42 MHz and L2 at 1227.60 MHz. Pseudo-range estimations from 'L1' and 'L2' are used to calculate Slant TEC (STEC) at a station. The empirical formula for calculating STEC from pseudo-range measurements is given below:

$$STEC = \frac{2}{k}\left[\frac{{f_1}^2{f_2}^2}{{f_1}^2 - {f_2}^2}\right](P_2 - P_1) + \tau^r + \tau^s$$

Equation 1

Where, 'k' is a constant whose value is 80.62 (m3/s2); 'f_1' and 'f_2' are frequencies of pseudo-ranges 'P_1' and 'P_1'; 'τ_r' and 'τ_s' are the differential code bias and inter-frequency bias corresponding to 'P_1' and 'P_2' (Kenpankho et al., 2011). Once STEC is corrected for the 'satellite bias and 'receiver bias', VTEC is calculated using the following formula:

$$VTEC = STEC\left\{cos\left[arcsin\left(\frac{R_e}{R_e + h_m}sin\chi\right)\right]\right\}$$

Equation 2

Where, χ is the zenith angle at receiver position, R_e is the mean radius of the earth and h_m is the height of ionospheric layer (Tariku, 2015).

2.5 International Reference Ionosphere (IRI)

IRI is an empirical model developed by the Committee on Space Research (COSPAR) and International Union of Radio Science (URSI) to provide standardized measurements of ionospheric parameters. A team of 60+ ionospheric experts from different parts of the world are responsible for generating the model, and introducing corrections or modifications for enhancing model accuracy. The inputs for this model are provided from a variety of instruments such as: a worldwide network of ionosondes, incoherent scatter radars, topside sounder satellites, and in-situ satellite measurements (Dieter et al., 2011). IRI was standardized by International Standardization Organization (ISO) in 2014. The model is developed based on experimental evidence rather than our evolving theoretical understanding of ionospheric plasma and its behaviour. Theoretical observations are only used to bridge whatever gaps are encountered in the development of this model. Therefore, if certain geographical areas and time periods do not have an underlying database of ionospheric research, then the ionospheric parameters estimated by IRI for that spatial and temporal extent have a risk of being mildly unreliable. For a given date, time and location, the IRI model estimates ion composition, electron density, VTEC, height of ionospheric layers, vertical ion drift and ion temperatures at various temporal resolutions.

2.6 Nequick-2 Model

NeQuick is based on the DGR profiler model, which was originally proposed by G. Di Giovanni and S. M. Radicella in 1990. The model empirically reproduces electron density profile of the ionosphere using the sum of Epstein layers (Sandro, 2009). The DGR model was designed to fulfil, to a reasonable extent, the basic criteria used to judge an empirical model of the ionosphere's electron density profile w.r.t. height. These criteria were first defined by Dudeney and Kressman in 1986, which state that mathematical formulations of ionospheric parameters should be simpler than traditional ionogram inversion techniques. In 1995, improvements to the original DGR model made by Radicella and Zhang allowed for estimation of VTEC (Sandro and Man-Lian, 1995). Further improvements and modifications were made to the original model in 2001, 2005 and 2006. These additions are reflected in the latest version of this model i.e. NeQuick-2. The NeQuick model has been particularly successful in estimating electron density of ionosphere above 100 km. The model is currently adopted by the European satellite navigation system (GALILEO) for ionospheric corrections of its single frequency GNSS operation. Further, the NeQuick model is adopted by International Telecommunication Union (ITU) as a suitable model for estimating ionospheric parameters (Ezquer et al., 2017). For a given date, time and location, the NeQuick model estimates electron density and VTEC at various temporal resolutions.

3. Method of Analysis

3.1 Data Download

GPS data was downloaded from the IGS data portal hosted by NASA at: ftp://cddis.nasa.gov/gnss/data/-daily/. From the data portal, 'observation files' with '.o' file extension can be downloaded for each day of the year. This data is available since 1992 for more than 300 geographic locations. To achieve the objectives of this study, '.o' files from GPS stations located at Lucknow and Hyderabad are downloaded for all days of 2015 and 2019. Download of '.o' files from IGS data portal was automated using Python script. Navigation message files, or '.n' files, which contain ephemeris for all the GPS satellites, were also downloaded from IGS data portal using a Python script. The hourly VTEC data from IRI-Plas and NeQuick 2 models can be obtained for a specific geographic location and hour. The IRI-Plas data was obtained by compiling and running the IRI-Plas source code, written in FORTRAN, which is available at ftp://ftp.izmiran.ru/pub/izmiran/SP-IM/ (Gulyaeva, 2020). The default values for all the parameters were used while running the IRI-Plas program. Similarly, the NeQuick-2 data was obtained by compiling and running the NeQuick-2 source code, written in FORTRAN, which is available at https://t-ict4d.ictp.it/nequick2/source-code (Zhang et al., 2010). Lower endpoint value of 0km, higher endpoint value of 20200km, and the daily solar index F10.7 values obtained from NASA OMNIWeb Data Explorer available at https://omniweb.gsfc.nasa.gov/form/dx1.html were used as parameters for running the NeQuick-2 program. The hourly VTEC data from both the models for Lucknow and Hyderabad for all days of 2015 and 2019 was thus obtained, and processed into a .csv (comma-separated values) file in our desired format.

3.2 Data Pre-Processing

GPS data downloaded from IGS data portal requires further pre-processing in order to extract VTEC values. Since each observation file represents data of one single day and one single station, around 1,460 observation files need to be downloaded for Lucknow and Hyderabad during 2015 and 2019. However, given that some data is missing, a total of 1179 observation files are downloaded using python script. TEC and satellite ephemeris data is compressed in observation and navigation files respectively in a Receiver Independent Exchange (RINEX) format. To extract this data, each RINEX observation and respective navigation file is provided as an input to the GPS-TEC software, designed by Dr. Gopi Seemala of the Indian Institute of Geomagnetism (https://seemala.blogsp-ot.com/). The output is a text file in standard text format, which provides in a column, VTEC values measured at one-minute intervals, for that day and location. A Python program was used to read data from the output files, which was processed to obtain hourly averaged VTEC values for all days of 2015 and 2019, at Lucknow and Hyderabad.

3.3 Data Processing

Once the data files with hourly-VTEC values from all three data sources are ready, they are used as an input to two python scripts: the first script is used to graphically represent diurnal variation of VTEC at Lucknow and Hyderabad during 2015 and 2019, using all three data sources; while the second script is used to generate a plot to represent relative deviation between modelled VTEC prediction and measured VTEC. The relative deviation (D) is calculated using the following formula:

$$D = \left[\frac{(Modelled\ VTEC - Measured\ VTEC)}{Measured\ VTEC}\right]$$

Equation 3

A third Python script is used to generate a scatter plot for the measured VTEC on X-axis, and modelled VTEC on Y-axis from IRI-Plas and NeQuick-2 in their respective plots. Linear regression analysis was performed on the data to determine the capability of both models in accurately producing VTEC data for the specific geographic locations during 2015 and 2019.

4. Results

4.1 Diurnal Variation and Relative Deviation (D) of Modelled and Measured VTEC at Lucknow During 2015

From Figure 1 and Figure 2 it can be observed that, at Lucknow, the relative deviation of modelled VTEC from measured VTEC is mostly positive throughout the year at all durations of the day. This indicates that, both IRI-Plas and NeQuick-2 models overestimate VTEC throughout the day at Lucknow during 2015. From Table 1 it can be observed that, at Lucknow, during 2015, the maximum relative deviation of modelled VTEC from measured VTEC was observed between 2100 UT and 2300 UT from February to October while using the IRI-Plas model. Similarly, while using the NeQuick-2 model, the maximum relative deviation was observed between 2100 UT and 2300 UT from February to August. However, during the remaining months of the year, the NeQuick-2 model shows maximum relative deviation from measured VTEC between 1300 UT and 1600 UT. In the month of November, both models show maximum relative deviation from measured VTEC at 1300 UT. Finally, the maximum relative deviation from measured VTEC for the entire year was observed in April at 2300 UT for both models.

From Table 1 it can further be observed that, at Lucknow, during 2015, the maximum relative deviation of modelled VTEC from measured VTEC during peak hours of ionization was observed in September (81.94%) while using IRI-Plas model; and in November (55.38%) while using NeQuick-2 model. Negative relative deviation from measured data was observed at peak hours of ionization in the months of March and July while using the NeQuick-2 model.

4.2 Diurnal Variation and Relative Deviation (D) of Modelled and Measured VTEC at Hyderabad During 2015

From Figure 3 and Figure 4 it can be observed that, at Hyderabad, during 2015, the relative deviation of modelled VTEC from measured VTEC is both positive and negative, depending on the duration of day and month. Throughout the year, the positive relative deviation or overestimation by modelled data is observed in the post-afternoon durations of the day. Low and negative relative deviation is observed predominantly in the sun-lit hours of the day. During certain months, the negative relative deviation or underestimation by modelled data extends to later UT. From Table 2 it can be observed that, at Hyderabad, during 2015, the maximum relative deviation of modelled VTEC from measured VTEC was observed between 2100 UT and 2300 UT, or 0000 UT, throughout the year while using IRI-Plas model.

Similarly, while using the NeQuick-2 model, the maximum relative deviation was observed between 2000 UT and 2300 UT, or 0000 UT, throughout the year. Finally, the maximum relative deviation from measured VTEC for the entire year was observed in March at 0000 UT for both models.

From Table 2 it can further be observed that, at Hyderabad, during 2015, the maximum relative deviation of modelled VTEC from measured VTEC during peak hours of ionization was observed in September (34.25%) while using IRI-Plas model; and in February (-22.96%) while using the NeQuick-2 model. Negative relative deviation from measured data was observed at peak hours of ionization in certain months while using both models. While negative relative deviation at peak hours of ionization was observed only in the months of February and March while using the IRI-Plas model, negative relative deviation at peak hours of ionization was observed almost throughout the year while using NeQuick-2 model.

4.3 Diurnal Variation and Relative Deviation (D) of Modelled and Measured VTEC at Lucknow During 2019

From Figure 5 and Figure 6 it can be observed that, at Lucknow, during 2019, the relative deviation of modelled VTEC from measured VTEC is both positive and negative during most months, with the exception of a few months (April, May, June and August) where positive relative deviation was observed at all durations of the day.

Table 1: Maximum relative deviation and relative deviation at peak hours of ionization between modelled and measured VTEC during 2015 at Lucknow

Month	**Maximum relative deviation while using IRI-Plas model (%)**	**Maximum relative deviation while using NeQuick-2 model (%)**	**Peak hours of ionization as observed from measured data**	**Relative deviation during peak hours of ionization while using IRI-Plas model**	**Relative deviation during peak hours of ionization while using NeQuick-2 model**
January	195.35 at 0000 UT	182.59 at 1600 UT	0700 UT	35.41 %	49.22 %
February	187.40 at 2100 UT	101.99 at 2100 UT	1000 UT	12.81 %	12.32 %
March	293.32 at 2300 UT	207.36 at 2000 UT	0800 UT	9.88 %	-4.62 %
April	426.71 at 2300 UT	392.92 at 2300 UT	0900 UT	22.94 %	17.21 %
May	385.35 at 2300 UT	351.19 at 2300 UT	0900 UT	20.90 %	11.94 %
June	380.13 at 2200 UT	362.13 at 2200 UT	0800 UT	20.65 %	11.96 %
July	319.40 at 2200 UT	210.44 at 2200 UT	0800 UT	17.83 %	-3.21 %
August	308.50 at 2300 UT	190.46 at 2300 UT	0700 UT	47.89 %	16.60 %
September	215.46 at 2300 UT	108.59 at 1400 UT	0900 UT	81.94 %	48.12 %
October	202.01 at 2100 UT	172.49 at 1400 UT	0700 UT	60.50 %	32.05 %
November	180.13 at 1300 UT	177.72 at 1300 UT	0600 UT	72.67 %	55.38 %
December	134.35 at 2000 UT	112.90 at 1500 UT	0900 UT	64.02 %	52.12 %

Table 2: Maximum relative deviation and relative deviation at peak hours of ionization between modelled and measured VTEC during 2015 at Hyderabad

Month	**Maximum relative deviation while using IRI-Plas model (%)**	**Maximum relative deviation while using NeQuick-2 model (%)**	**Peak hours of ionization as observed from measured data**	**Relative deviation during peak hours of ionization while using IRI-Plas model**	**Relative deviation during peak hours of ionization while using NeQuick-2 model**
January	196.21 at 2300 UT	140.36 at 2200 UT	0800 UT	14.20 %	6.70 %
February	188.08 at 2200 UT	132.34 at 2200 UT	1000 UT	-11.44 %	-22.96 %
March	1239.1 at 0000 UT	846.86 at 0000 UT	1000 UT	-3.66 %	-17.97 %
April	758.12 at 0000 UT	681.46 at 0000 UT	1000 UT	0.95 %	-13.32 %
May	217.41 at 2300 UT	178.66 at 2300 UT	0900 UT	20.11 %	-2.73 %
June	182.76 at 2100 UT	167.84 at 2100 UT	0800 UT	21.81 %	-0.44 %
July	261.62 at 2200 UT	158.72 at 2200 UT	0900 UT	26.11 %	-7.86 %
August	132.07 at 2100 UT	88.29 at 2000 UT	0900 UT	28.26 %	-7.29 %
September	234.94 at 2200 UT	121.11 at 2100 UT	1000 UT	34.25 %	1.82 %
October	247.29 at 2300 UT	119.87 at 2100 UT	0900 UT	28.88 %	-0.31 %
November	243.84 at 2200 UT	148.22 at 2100 UT	0900 UT	25.16 %	2.47 %
December	303.40 at 0000 UT	166.53 at 2000 UT	0900 UT	28.57 %	11.06 %

Table 3: Maximum relative deviation and relative deviation at peak hours of ionization between modelled and measured VTEC during 2019 at Lucknow

Month	**Maximum relative deviation while using IRI-Plas model (%)**	**Maximum relative deviation while using NeQuick-2 model (%)**	**Peak hours of ionization as observed from measured data**	**Relative deviation during peak hours of ionization while using IRI-Plas model**	**Relative deviation during peak hours of ionization while using NeQuick-2 model**
January	161.05 at 0600 UT	114.98 at 0600 UT	0800 UT	122.29 %	82.41 %
February	175.29 at 0700 UT	119.35 at 0700 UT	0900 UT	108.57 %	72.74 %
March	144.63 at 0600 UT	112.49 at 0600 UT	0800 UT	131.81 %	100.95 %
April	780.58 at 0000 UT	492.83 at 0000 UT	0800 UT	119.25 %	91.40 %
May	135.37 at 1000 UT	116.39 at 1000 UT	0900 UT	123.36 %	97 %
June	159.83 at 2100 UT	93.28 at 1900 UT	0700 UT	83.07 %	44.65 %
July	N.A.	N.A.	N.A.	N.A.	N.A.
August	135.97 at 0700 UT	91.13 at 0900 UT	0800 UT	129.53 %	82.76 %
September	145.25 at 0300 UT	92.57 at 0300 UT	0700 UT	91.93 %	54.45 %
October	174.80 at 0200 UT	128.13 at 1200 UT	0800 UT	95.85 %	72.10 %
November	N.A.	N.A.	N.A.	N.A.	N.A.
December	193.52 at 0700 UT	142.48 at 0700 UT	0900 UT	130.38 %	95.16 %

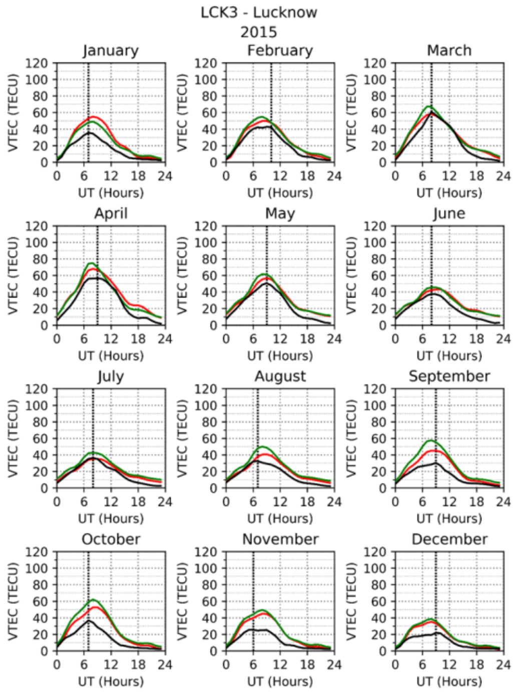

Figure 1: Diurnal variation of modelled and measured VTEC at Lucknow during 2015. The black, green and red solid lines denote VTEC derived from GPS, IRI-Plas and NeQuick-2 respectively. The vertical black dashed line denotes the peak hour of ionization as observed from measured data

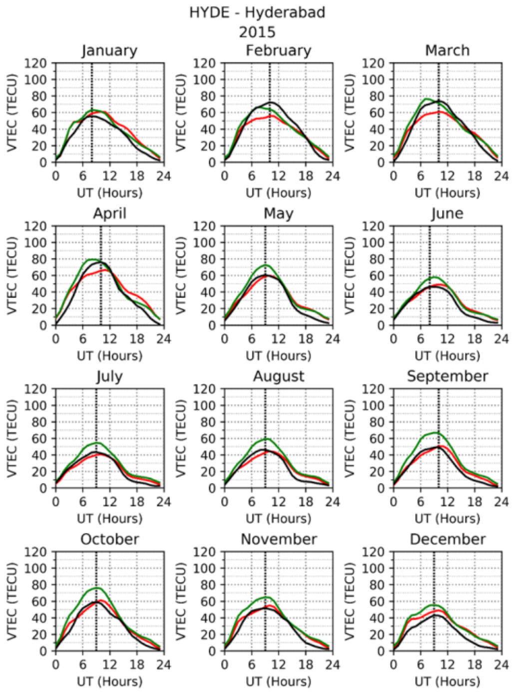

Figure 3: Diurnal variation of modelled and measured VTEC at Hyderabad during 2015. The black, green and red solid lines denote VTEC derived from GPS, IRI-Plas and NeQuick-2 respectively. The vertical black dashed line denotes the peak hour of ionization as observed from measured data.

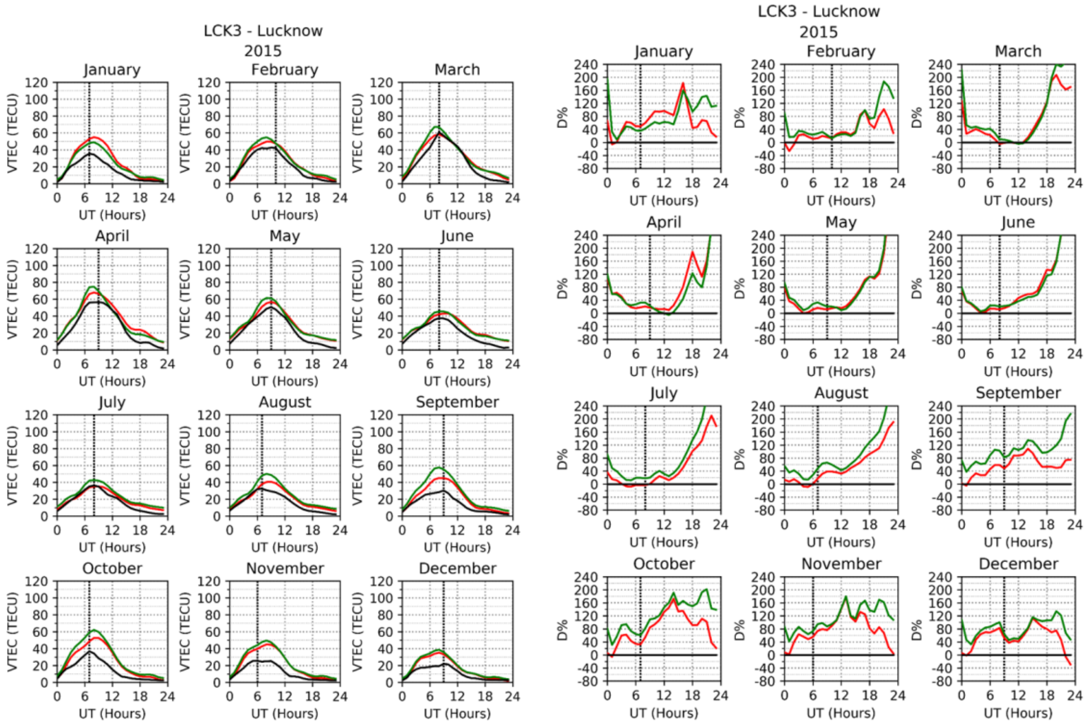

Figure 2: Relative deviation of modelled and measured VTEC at Lucknow during 2015. The green and red solid lines denote relative deviation from the measured data while using IRI-plas and NeQuick-2 respectively. The vertical black dashed line denotes the peak hour of ionization as observed from measured data

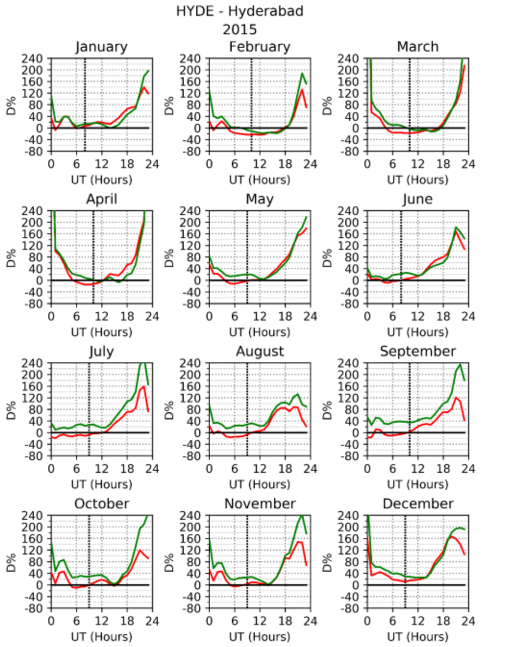

Figure 4: Relative deviation of modelled and measured VTEC at Hyderabad during 2015. The green and red solid lines denote relative deviation from the measured data while using IRI-plas and NeQuick-2 respectively. The vertical black dashed line denotes the peak hour of ionization as observed from measured data

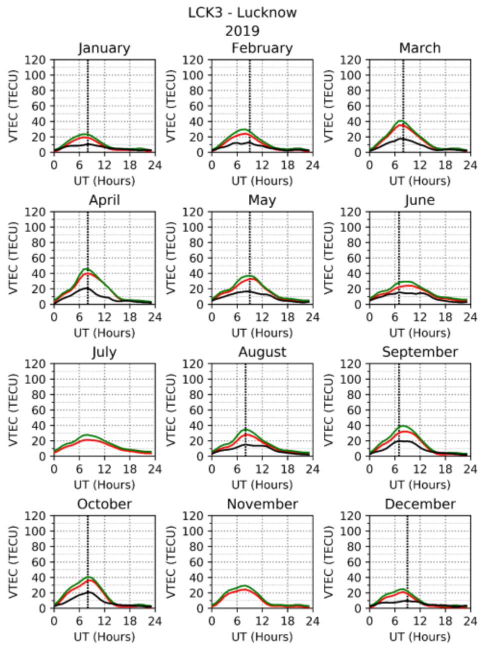

Figure 5: Diurnal variation of modelled and measured VTEC at Lucknow during 2019. The black, green and red solid lines denote VTEC derived from GPS, IRI-Plas and NeQuick-2 respectively. The vertical black dashed line denotes the peak hour of ionization as observed from measured data

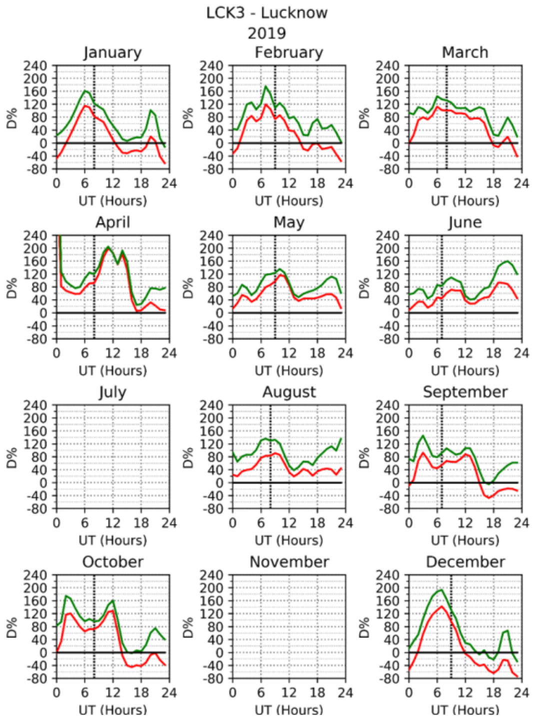

Figure 6: Relative deviation of modelled and measured VTEC at Lucknow during 2019. The green and red solid lines denote relative deviation from the measured data while using IRI-plas and NeQuick-2 respectively. The vertical black dashed line denotes the peak hour of ionization as observed from measured data

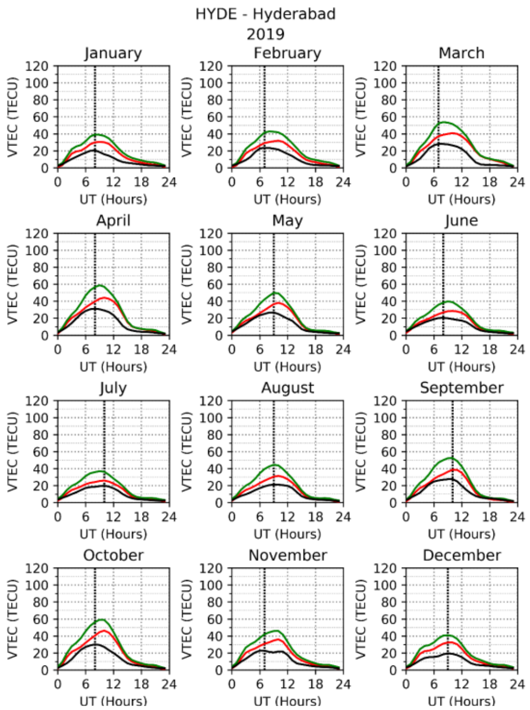

Figure 7: Diurnal variation of modelled and measured VTEC at Hyderabad during 2019. The black, green and red solid lines denote VTEC derived from GPS, IRI-Plas and NeQuick-2 respectively. The vertical black dashed line denotes the peak hour of ionization as observed from measured data

Table 4: Maximum relative deviation and relative deviation at peak hours of ionization between modelled and measured VTEC during 2019 at Hyderabad

Month	Maximum relative deviation while using IRI-Plas model (%)	Maximum relative deviation while using NeQuick-2 model (%)	Peak hours of ionization as observed from measured data	Relative deviation during peak hours of ionization while using IRI-Plas model	Relative deviation during peak hours of ionization while using NeQuick-2 model
January	163.74 at 1300 UT	109.24 at 1300 UT	0800 UT	89.71 %	45.29 %
February	186.54 at 1800 UT	102.80 at 1800 UT	0700 UT	76.46 %	23.71 %
March	248.94 at 1600 UT	237.81 at 1600 UT	0700 UT	85.48 %	32.24 %
April	144.41 at 1400 UT	123.04 at 1400 UT	0800 UT	81.23 %	26.77 %
May	99.32 at 1100 UT	69.19 at 1200 UT	0900 UT	85.72 %	36.58 %
June	104.87 at 1000 UT	55.10 at 1100 UT	0800 UT	86.94 %	30.61 %
July	98.77 at 2100 UT	60.89 at 1400 UT	1000 UT	82.52 %	30.44 %
August	108.83 at 0900 UT	55.16 at 1500 UT	0900 UT	108.83 %	43.29 %
September	127.26 at 1300 UT	89.46 at 1300 UT	1000 UT	89.50 %	39.8 %
October	146.16 at 0200 UT	89.82 at 0200 UT	0800 UT	86.57 %	34.17 %
November	134.05 at 1400 UT	86.38 at 1400 UT	0700 UT	83.48 %	34.73 %
December	129.31 at 0700 UT	73.43 at 1500 UT	0900 UT	109.20 %	65.08 %

The negative relative deviation from measured data is mostly observed in the post-afternoon durations of the day, and in some months (January, February and December) it is observed between 0000 UT and 0300 UT. Furthermore, GPS data from the IGS portal is unavailable for the months of July and November.

From Table 3 it can be observed that, at Lucknow, during 2019, the maximum relative deviation of modelled VTEC from measured VTEC was observed at different durations of time at different months of the year. However, in all months of the year except June, August and October, both models show maximum relative deviations from measured VTEC at the same UT. Finally, the maximum relative deviation from measured VTEC for the entire year was observed in April at 0000 UT for both models. From Table 3 it can further be observed that, at Lucknow, during 2019, the maximum relative deviation of modelled VTEC from measured VTEC during peak hours of ionization was observed in March while using IRI-Plas (131.81%) and NeQuick-2 (100.95%) models. Negative relative deviation from measured data was not observed at peak hours of ionization at Lucknow during 2019.

4.4 Diurnal Variation and Relative Deviation (D) of Modelled and Measured VTEC at Hyderabad During 2019

From Figure 7 and Figure 8 it can be observed that, at Hyderabad, during 2019, the relative deviation of modelled VTEC from measured VTEC is both positive and negative, depending on the duration of day. Throughout the year, positive relative deviation is observed in the earliest hours of the day, and throughout the sunlit hours of the day. Furthermore, throughout the year, negative relative deviation is mostly observed in the post-sunset duration of the day. Negative relative deviation is also observed between 0000 UT and 0200 UT throughout the year.

From Table 4 it can be observed that, at Hyderabad, during 2019, the maximum relative deviation of modelled VTEC from measured VTEC was observed at different durations of time at different months of the year. However, in all months of the year except July, August and December, both models show maximum relative deviations from measured VTEC at approximately the same UT. Finally, the maximum relative deviation from measured VTEC for the entire year was observed in March at 1600 UT for both models. From Table 4 it can further be observed that, at Hyderabad, during 2019, the maximum relative deviation of modelled VTEC from measured VTEC during peak hours of ionization was observed in December while using IRI-Plas (109.2%) and NeQuick-2 (65.08%) models. Negative relative deviation from measured data was not observed at peak hours of ionization at Hyderabad during 2019.

5. Discussions

At the mid-latitude region of Lucknow and the low-latitude region of Hyderabad, the maximum relative deviation of modelled VTEC from measured VTEC has a higher magnitude while using IRI-Plas model for all months of 2015 and 2019. While the maximum relative deviation for the entire year at Lucknow was observed in April for both years, the same was observed in March at Hyderabad during 2015 and 2019. During the peak hours of ionization, when electron content in the ionosphere is at its highest due to increased solar radiation, the magnitude of relative deviation of modelled VTEC from measured VTEC is higher while using IRI-Plas model at both regions during 2019.

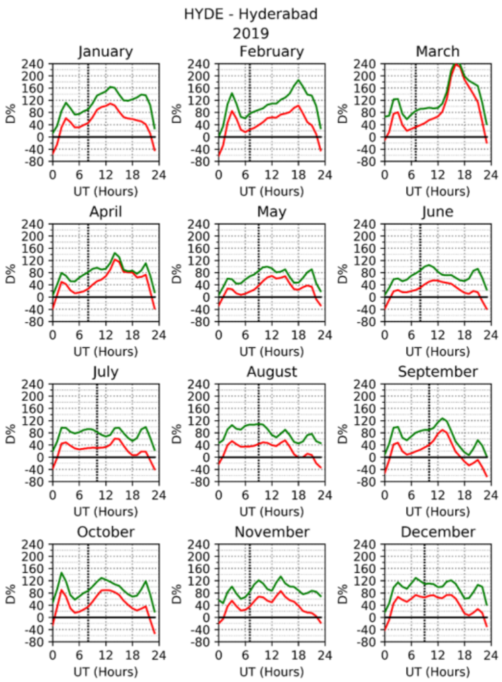

Figure 8: Relative deviation of modelled and measured VTEC at Hyderabad during 2019. The green and red solid lines denote relative deviation from the measured data while using IRI-plas and NeQuick-2 respectively. The vertical black dashed line denotes the peak hour of ionization as observed from measured data

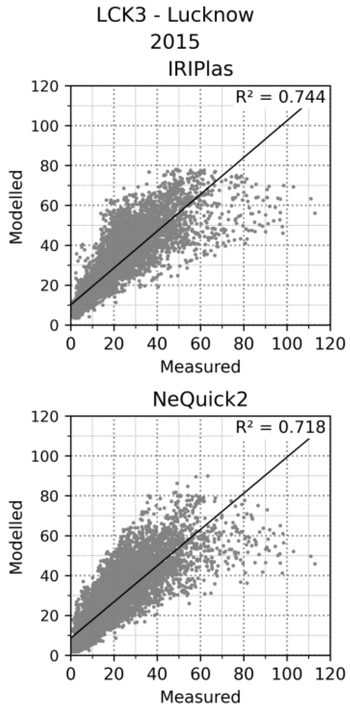

Figure 9: Scatter plot of modelled vs measured VTEC at Lucknow during 2015

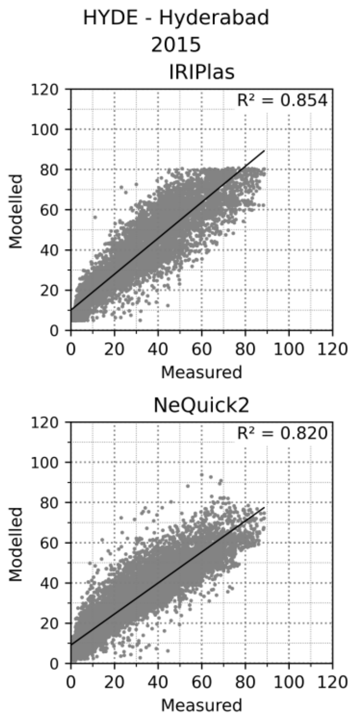

Figure 10: Scatter plot of modelled vs measured VTEC at Hyderabad during 2015

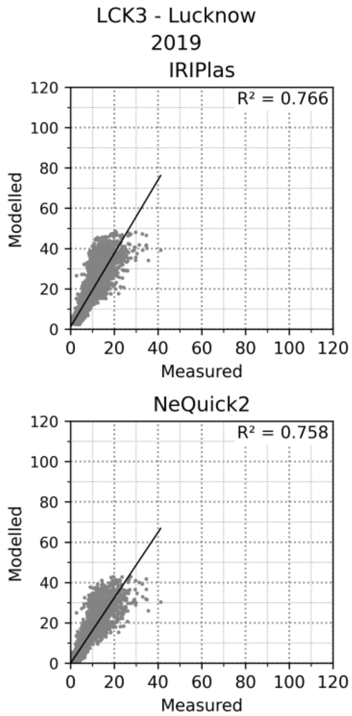

Figure 11: Scatter plot of modelled vs measured VTEC at Lucknow during 2019

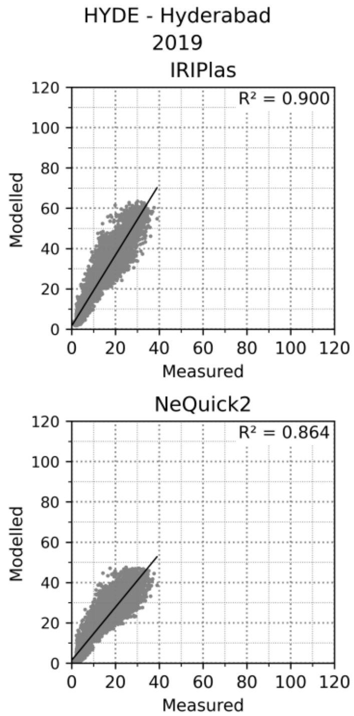

Figure 12: Scatter plot of modelled vs measured VTEC at Hyderabad during 2019

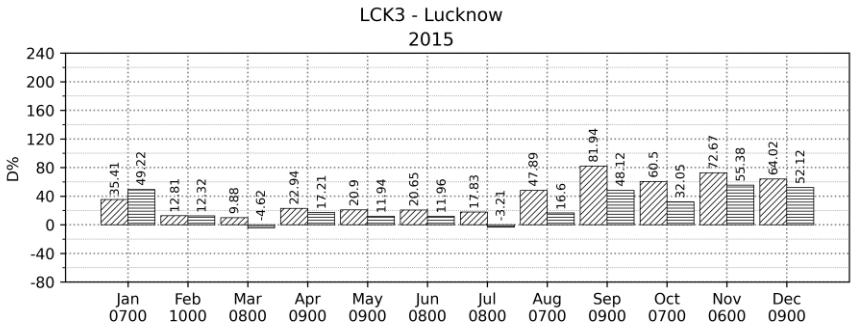

Figure 13: %D at peak hours of ionization for all months of 2015 at Lucknow. Relative deviation of IRI-Plas and NeQuick-2 data from measured VTEC is denoted by diagonally-hatched and horizontally-hatched bar plots respectively

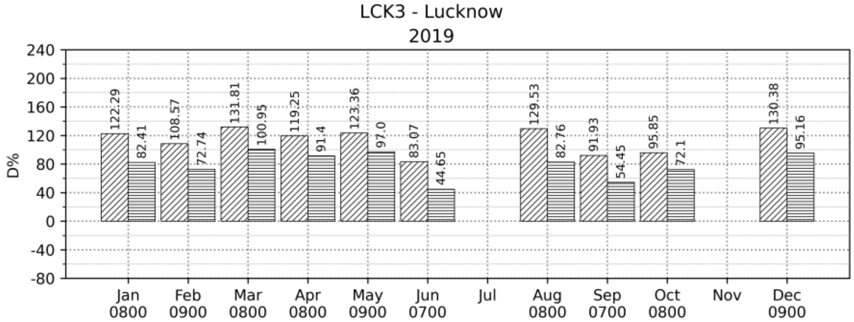

Figure 14: %D at peak hours of ionization for all months of 2019 at Lucknow. Relative deviation of IRI-Plas and NeQuick-2 data from measured VTEC is denoted by diagonally-hatched and horizontally-hatched bar plots respectively

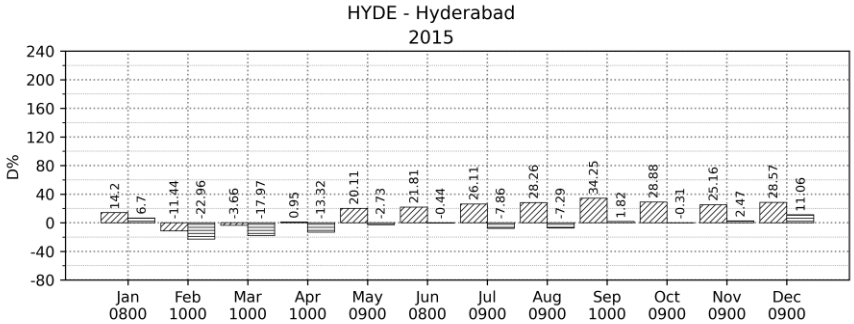

Figure 15: %D at peak hours of ionization for all months of 2015 at Hyderabad. Relative deviation of IRI-Plas and NeQuick-2 data from measured VTEC is denoted by diagonally-hatched and horizontally-hatched bar plots respectively

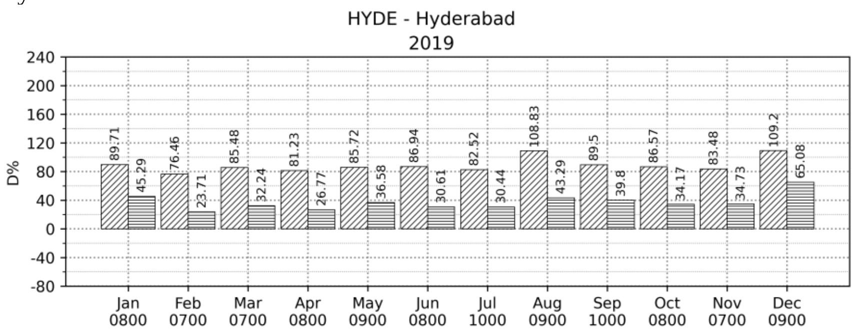

Figure 16: %D at peak hours of ionization for all months of 2019 at Hyderabad. Relative deviation of IRI-Plas and NeQuick-2 data from measured VTEC is denoted by diagonally-hatched and horizontally-hatched bar plots respectively

While the same observation holds true at Lucknow during 2015, the magnitude of relative deviation from measured data has a higher magnitude while using the NeQuick-2 model at Hyderabad in the months of February, March and April of 2015. Furthermore, during peak hours of ionization at both regions, negative relative deviation was not observed in any month of 2019. Considerable negative relative deviation during peak hours of ionization was only observed in Hyderabad during 2015 while using the NeQuick-2 model. Also, the magnitude of relative deviation at peak hours of ionization is higher during 2019 in both regions for both models, when compared to relative deviation of modelled data at peak hours of ionization during 2015 for the respective regions.

Finally, from Figures 9, 10, 11 and 12 it can be observed that the IRI-Plas data shows higher R^2 value when compared to NeQuick-2 data for both years and at both regions. Furthermore, at both regions, R^2 value is higher during 2019.

6. Conclusions

From the above study the following conclusions are made:

- The magnitude of maximum relative deviation of modelled VTEC from measured VTEC was higher while using IRI-Plas model at Lucknow and Hyderabad during all months solar maximum and solar minimum. At Lucknow, the maximum relative deviation for the entire year was recorded in April during solar minimum and maximum. However, at Hyderabad, the same result was recorded in March during solar minimum and maximum. The above-mentioned characteristics of maximum relative deviation at both geographic locations seem to be unaltered by the effects of solar maxima and minima.
- From Figures 13, 14, 15 and 16 it can be summarized that, during the peak hours of ionization, magnitude of relative deviation of modelled VTEC from measured VTEC was higher while using IRI-Plas model for both years at both regions, except for three months of 2015 at Hyderabad. The above-mentioned characteristics of relative deviation during peak hours of ionization at both geographic locations seem to be unchanged by the effects of solar maxima and minima. Negative relative deviation of modelled data during peak hours of ionization is observed only during solar maximum at certain months. Considerable underestimation of VTEC during peak hours of ionization was only observed in Hyderabad during the solar maximum while using the NeQuick-2 model. Furthermore, the magnitude of relative deviation of modelled data during peak hours of ionization is higher during solar minimum at both regions for both models. Therefore, it can be concluded that, during solar minimum, VTEC is highly overestimated by both models during peak hours of ionization, and the magnitude of overestimation at these hours is higher while using IRI-Plas model for both regions. During the solar maximum, VTEC at the mid-latitude region of Lucknow during peak hours of ionization showed maximum relative deviation during the September Equinox and December Solstice seasons, while using both models (Figure 13). However, during the same year, while VTEC at the low-latitude region of Hyderabad during peak hours of ionization showed maximum deviation during June Solstice, September Equinox and December Solstice seasons when using IRI-Plas model, the same was observed while using NeQuick-2 model in the March Equinox season (Figure 15). Finally, during solar minimum, At Lucknow and Hyderabad, VTEC is highly overestimated by both models throughout the year. However, NeQuick-2 model was more accurate in predicting VTEC during peak hours of ionisation of solar minimum, especially at the low-latitude region of Hyderabad (Figure 15 and Figure 16).
- The coefficient of determination (R^2) values were high during solar minimum while using both models at both regions. This implies that both models show smaller differences when compared to measured VTEC at both geographic locations during solar minimum. Furthermore, the IRI-Plas model produces a more accurate representation of VTEC when compared to NeQuick-2 model during solar minimum and maximum. Finally, R^2 value at Hyderabad is higher than that at Lucknow during solar minimum and maximum. This indicates that, both models produce electron content at a low-latitude region more accurately, than at a mid-latitude region in India.

Acknowledgements

The authors would like to express their gratitude to the International Multilateral Regional Cooperation Division, Department of Science and Technology, Government of India for grant (IMRC/AISTDF/CRD/2018/000037) towards this project on ionospheric studies over Indian subcontinent. The authors extend their gratitude to

NASA and IGS for providing the required datasets to conduct this research. We would like to sincerely acknowledge the authors responsible for the design and implementation of the IRI-Plas model (Gulyaeva et al., 2012, 2013, 2017 and 2018) (Gulyaeva, 2016 and 2019). Similarly, we would like to extend our acknowledgement to the Aeronomy and Radio-propagation Laboratory of the Abdus Salam International Centre for Theoretical Physics, Trieste, Italy; and the authors (Bruno Nava, Pierdavide Coisson, Johanna Wagner and Yenca Migoya Orue) responsible for the implementation of the NeQuick-2 model.

References

Anderson, A., Anghel, A., Chau, J., Yumoto, K., Battacharyya, A. and Alex, S., 2006, *Daytime, Low Latitude, Vertical ExB Drift Velocities, Inferred from Ground-Based Magnetometer Observations in the Peruvian, Philippine and Indian Longitude Sectors Under Quiet and Disturbed Conditions*. ILWS Workshop, Goa. 19-24.

Appleton, E. V., 1946, Two Anomalies in the Ionosphere. *Nature*, Vol. 157, 691-693.

Bauer, S. J. and Daniels, F. B., 1959, Measurements of Ionospheric Electron Content by the Lunar Reflection Technique. *J. Geophys. Res*., 64, 1371- 1376.

Bhattacharya, S., Purohit, P. K. and Gwal, A. K., 2009, Ionospheric Time Delay Variations in Equatorial Anomaly Region During Low Solar Activity Using GPS. *Indian J. Radio Space Phys*., Vol. 38, 266-274.

Bilitza, D., 1990, *International Reference Ionosphere 1990, NSSDC/ WDC-A-R&S 90-22*. National Space Science Data Center, Greenbelt.

Bilitza, D., Radicella, S., Reinisch, B., Adeniyi, J., Mosert, M., Zhang, S. and Obrou, O., 2000, New B0 and B1 Models for IRI. *Adv Space Res*, Vol. 25(1), 89-95.

Bilitza, D. and Reinisch, B. W., 2008, International Reference Ionosphere 2007: Improvements and New Parameters. *Adv Space Res.*, Vol. 42(4), 599-609. doi:10.1016/j.asr.2007.07.048.

Chauhan, V. and Singh, O. P., 2010, A Morphological Study of GPS-TEC Data at Agra and their Comparison with the IRI Model. *Adv. Space Res.*, Vol. 46, 280-290.

David, H. H., 2015, The Solar Cycle. *Living Rev. Solar Phys.*, Vol. 7(1), 12.

Dieter, B., Lee-Anne, M., Bodo, R. and Tim, F., 2011, The International Reference Ionosphere Today and in the Future. *J. Geod*, Vol. 85, 909-920.

D'ujanga, F. M., Mubiru, J., Twinamasiko, B. F., Basalirwa, C. and Ssenyonga, T. J., 2012, Total Electron Content Variations in Equatorial Anomaly Region. *Adv. Space Res*. Vol. 50, 441-449.

Evans, J. V., 1957, The Electron Content of the Ionosphere. *J. Atmos. Terr. Phys*., Vol. 11, 259-271.

Ezquer, R. G., Scida´, L. A., Migoya Orue´, Y., Nava, B., Cabrera, M. A. and Brunini, C., 2017, NeQuick 2 and IRI Plas VTEC Predictions for Low Latitude and South American Sector. *Advances in Space Research*, Vol. 61(7), 1803-1818.

Gulyaeva, T. L. and Bilitza, D., 2012, *Towards ISO Standard Earth Ionosphere and Plasmasphere Model. In: "New Developments in the Standard Model*". edited by R.J.Larsen, 1-39, NOVA, Hauppauge, New York, [Available at https://www.novapublishers.com/catalog/product_info.php?products_id=35812]

Gulyaeva, T. L., Arikan, F., Hernandez-Pajares, M., Stanislawska, I., 2013, GIM-TEC Adaptive Ionospheric Weather Assessment and Forecast System. *J. Atmosph. Solar-Terr. Phys.*, Vol. 102, 329-340, doi:10.1016/j.jastp.2013.06.011.

Gulyaeva, T., 2016, Modification of the Solar Activity Indices in the International Reference Ionosphere IRI and IRI-Plas Models Due to Recent Revision of Sunspot Number Time Series. *Solnechno-Zemnaóa Fizika*. Vol. 2(3), 59-68. DOI:10.12737/20872. [Available at: http://ru.iszf.irk.ru/Journal_Solar-Terrestrial-_Physics._Vol._2%2C_Iss._3%2C_2016 (in English)].

Gulyaeva, T. L., Arikan, F., Poustovalova L., Sezen U., 2017, TEC Proxy Index of Solar Activity for the International Reference Ionosphere IRI and its Extension to Plasmasphere IRI-PLAS Model. *Int. J. Sci. Eng. Applied Sci*., Vol. 3(5),144-150, http://ijseas.com/index.php/issue-archive-2/volume3/issue-5/.

Gulyaeva, T. L., Arikan, F., Sezen, U. and Poustovalova, L. V., 2018, Eight Proxy Indices of Solar Activity for the International Reference Ionosphere and Plasmasphere Model. *J. Atmos. Solar-Terr. Phys*., Vol. 172, 122-128, https://doi.org/10.1016/j.jastp.2018.03.025.

Gulyaeva, T. L., 2019, Predicting Indices of the Ionosphere Response to Solar Activity for the Ascending Phase of the 25th Solar Cycle. *Adv. Space Res.*, Vol. 63,(Is.5), 1588-1595, https://doi.org/10.1016/j.asr.2018.11.002.

Gulyaeva, T. L., 2020, IRI-Plas (version IRI-Plas-2017) [Source code]. ftp://ftp.izmiran.ru/pub-/izmiran/SPIM/.

Kenpankho P., Watthanasangmechai, K., Supnithi, P., Tsugawa, T. and Maruyama, T., 2011, Comparison of GPS TEC Measurements with IRI TEC Prediction at the Equatorial Latitude Station, Chumphon, Thailand. *Earth Planets Space*, Vol. 63, 365-370.

Kouba J., 2009, A Guide to Using International GNSS Service (IGS) Products. *Natural Resources Canada*. 1-34.

Mendillo, M., 2005, Storms in the Ionosphere: Patterns and Processes for Total Electron Content. *Rev. Geophys.*, Vol. 44, RG4001.

Okoh, D., Mckinnell, L., Cilliers, P. and Okere, B., 2015, IRI-vTEC Versus GPS-vTEC for Nigerian SCINDA GPS Stations. Advances in Space Research, Vol. 55(8), 1941-1947.

Sandro, R. and Man-Lian, Z., 1995, The Improved DGR Analytical Model of Electron Density Height Profile and Total Electron Content in the Ionosphere. Annals of geophysics, Vol. 38(1), 35-41.

Sandro, R., 2009, The NeQuick Model Genesis, Uses and Evolution. *Annals of Geophysics*, Vol. 52(3/4), 417-422.

Tariku, Y. A., 2015, TEC Prediction Performance of IRI-2012 Model During a Very Low and a High Solar Activity Phase Over Equatorial Regions, Uganda. *J. Geophys. Res. Space Physics*, Vol. 120, 5973-5982.

Unnikrishnan, K., Balachandran, R. and Venugopal, C., 2002, A Comparative Study of Nighttime Enhancements of TEC at Low Latitude Station on Storm and Quiet Nights Including the Local Time, Seasonal and Solar Activity Dependence. *Ann. Geophys*. Vol. 20, 1843-1850.

Zhang, M. L., Radicella, S. M., Leitinger, R., Nava, B., Coisson, P., Wagner, J. and Orue, Y. M., 2010, Aeronomy and Radiopropagation Laboratory of the Abdus Salam International Centre for Theoretical Physics, Trieste, Italy (2010) NeQuick-2 (version 2.0.2) [Source code]. https://t-ict4d.ictp.it/nequick2/source-code.