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ORIGINAL RESEARCH

THE ASSESSMENTS OF IRI-2016, IRI-Plas2017 and NeQuick-2 MODELS USING GPS-TECIN THE AUSTRALIAN LONGITUDE SECTOR DURING SOLAR CYCLE 24

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Abstract:

Introduction: Ionospheric modelling is very crucial in ionospheric studies because of paucity in data in regions where ionospheric instruments such as Global Positioning System (GPS) receivers, ionosonde/digisonde, etc., are hardly available.

Aim: In this research, the assessment of GPS-TEC using three ionospheric models namely: IRI-2016, IRI-Plas2017 and NeQuick-2 models in the Australian longitude sector (DAV1) for the period of 2011 – 2017 was studied**.**

Materials and Methods: Hourly mean values of Total Electron Content (TEC) obtained from the GPS receiver at DAV1 station, and some ionospheric models were used to analyze the diurnal and seasonal variations in TEC. The prediction capability of the ionospheric models using annual Root Mean Square Errors (RMSE) and annual Mean Absolute Errors (MAE) between GPS-TEC and the ionospheric models were used to assess the performances of the ionospheric models.

Results: Results obtained shows highest TEC values (~42 TECU) around 5:00UT corresponding to noontime (12:00LT) and at 09:00UT corresponding to post-noon (14:00LT) hours while lowest TEC values ~2 TECU were recorded at 18:00UT (01:00LT) and at 22:00UT (05:00LT) hours of the day. The results also show higher TEC values during the equinoxes than the solstices, except for the December solstice which recorded almost equal magnitude of TEC values as observed in the equinoxes.

Conclusion: Generally, this study shows that the IRI-Plas 2017model had better performance than both the IRI-2016 the NeQuick-2models throughout the study period, showing least RMSE and MAE values in most seasons

Keywords: GPS-TEC; IRI-2016; IRI-Plas 2017; NeQuick-2; RMSE and MAE.

1. INTRODUCTION

The ionosphere is one of the major sources of error on the propagation path of satellite radio signal, as a result of the presence of electrons [1]. This error poses different degrees of inaccuracies to space-based communications and navigation systems [2]. Hence, the transformation of highly dynamic technological satellite-based/navigation systems is accelerating the interest of scientists in ionospheric research. In the past decade, ionospheric modeling and related studies that aim to understand the evolution of the ionosphere through time and space have received significant attention in ionospheric research [3]. Ionospheric modeling is useful in forecasting/nowcasting the ionosphere's activity for regions and times where actual ground and space-based observation data are not accessible [4]. Also, understanding how correctly ionospheric model users can forecast some useful ionospheric parameters is a critical concern. The estimation of model errors by calculating its predictions alongside equivalent instrumental data have been an accepted method to assess the accuracy of ionospheric models. Presently, there are differentgroups of scientists globally that are involved in Ionospheric modeling [5]. Some of the already existing models include but are not limited to the international reference ionosphere (IRI), NeQuick models, etc. After building ionospheric models, some of these scientists are also engaged in the frequent updates of these models over time for various applications, as a result of the changing ionospheric morphology. However, with the increasing numbers of Global Navigation Satellite Systems (GNSS) receivers and other ionospheric instruments such as the ionosonde, Incoherent Scatter Radar (ISR) etc., there are now widely used ground- and space-based ionospheric data for ionospheric research and applications. [6].

In recent years, the Global Positioning System (GPS) receiver has become a commonly used instrument for monitoring the ionosphere on both regional and global scale [7]. It has given researchers a new set of tools for studying ionospheric abnormalities and their consequences on radio wave propagation. [8] presented in their work that we can estimate TEC from dual-frequency GPS receivers.

The limits of the IRI model's altitude range of ~ 2000km above the Earth's surface is frequently disregarded while analyzing and estimating GPS-TEC, and in comparism to the IRI model. However, under certain circumstances, the plasmaspheric contribution to the GPS-TEC can become large, which was investigated by [9]. However, there are reports of some limitations in the appropriate forecasting capabilities of most existing ionospheric models. For example, according to [10], IRI-2016 overestimated/underestimated TEC values mostly at high latitudes during the four seasons. [11] reported that IRI-2016 model mostly underestimates TEC values, particularly during the daytime (12:00–18:00 LT) at three separate stations in Turkey. Furthermore, [12] reported in their work that, since the IRI model is limited to altitude of ~2,000 km, an increasing number of researchers have concentrated on extending their research to the plasmasphere. An empirical ionospheric model which extends to the plasmasphere up to 20,200km altitude was proposed using the international reference ionosphere (IRI-Plas) [13].

Another common ionospheric model is the NeQuick model. The NeQuick model is a trans-ionospheric application-friendly empirical quick-run ionospheric model that produces electron density for specific space, time, and solar activity circumstances from a minimum set of anchor point characteristics. In order to calculate the slant TEC between a particular user location and the spacecraft in view, NeQuick is used in conjunction with integration techniques along the satellite-to-receiver link [14]. Furthermore, the NeQuick model is a fast-run model that uses numerical integration to calculate the TEC and electron density [15].

Efforts have been made in the past to predict the true state of the ionosphere using ionospheric models by adopting a single metric approach to ascertain the level of prediction of the models, for example, [1], [2], [5], [6], [7], [8], [12], [13], [18], [19], [20], [21], [22], [23], [24], [25], [27], [29], and [33]. However, the outcome of these research studies shows some limitations in the forecasting capability of the ionospheric models in regions other thanthe Australian belt. Hence, the aim of this research is to assess GPS-TEC using some ionospheric modelssuch as IRI-2016, IRI-Plas 2017 and NeQuick-2 models for the period of 2011 – 2017 at a GPS station

(DAV1) located in the Australian territory. DAVIS (DAV1) is a high-latitude station in the southernhemisphere. Although, few research in the past reported inadequate forecasting capability of ionospheric models in the Australian region [33]. This research also intends to investigate the possible causes of these inaccuracies in the forecasting strength of the mentioned ionospheric models in this region.

2. MATERIAL AND METHODOLOGY

In this research, GPS-TEC and TEC data extracted from ionospheric models namely: IRI-2016, IRI-Plas 2017 and NeQuick-2 were used. The region of interest is a station located in the Australian territory (DAV1), with geographic longitude and latitude of 77.98°E, 68.58°S, respectively, and geomagnetic longitude and latitude of 132.35°E, 75.9°S, respectively. GPS-TEC data was obtained from the University NAVSTAR Consortium (UNAVCO) website (http://www.unavco.org). The hourly TEC values of IRI-2016 were obtained from the Community Coordinating Modeling Center (CCMC) website (https://ccmc.gsfc.nasa.gov/modelweb/models/iri2016_vitmo.php). The IRI-Plas 2017 computes TEC data up to a height of 20,200 km. Also, hourly TEC values for the IRI-Plas 2017 model were obtained using the windows executable program from the website of the IZMIRAN Institute (http://ftp.izmiran.ru/pub/izmiran/SPIM/) [6]. Furthermore, hourly TEC values of NeQuick-2 were obtained using the windows executable program created from the FORTRAN source code, which was obtained from the Ionosphere Radio Propagation Unit of the T/ICT4D Laboratory (https://t-ict4d.ictp.it/nequick2/source code).GPS-TEC were downloaded in Receiver Independent Exchange (RINEX) format and were processed using GPS-TEC analysis software (GPS_Gopi_v3.03), designed and developed by Gopi Seemala of the Indian Institute of Geomagnetism and accessible from his webpage (https://seemala.blogspot.com). The GPS-TEC application software reads raw data from the RINEX file, processes cycle slips, multipath, and scintillations, and then produces output TEC values [20]. According to [20], an elevation cut-off angle greater than 70° is required for an ionospheric shell height of about 350km for the high-latitude region of the ionosphere.

GPS-TEC obtained from the GPS-TEC analysis software are in per minute sequence, which were averaged to hourly TEC values using equation 1. Also, equation 1 was used to convert hourly TEC values of IRI-2016, IRI-Plas 2017 and NeQuick-2 models to monthly TEC values.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} (TEC_i) \qquad (1)$$

[1], [5], [12], [13], [22], [23], also made use of equation (1) to investigate the diurnal variations in TEC in different GPS stations around the world.

The hourly values of GPS-TEC, IRI-2016, IRI-Plas 2017 and NeQuick-2 were used to study the diurnal variations in TEC. Furthermore, the hourly TEC values were averaged to daily values and further averaged to monthly values. The monthly TEC values were further grouped into the four seasons namely: March equinox (February, March, and April), June solstice (May, June, and July), September equinox (August, September, and October) and December solstice (November, December, and January) as shown in Table 1, in order to analyze the seasonal variations in TEC.

Table 1: The four Seasons of the year with their corresponding months.

S/N	Seasons	Months
1	*March Equinox*	*February, March, April*
2	*June Solstice*	*May, June, July*
3	*September Equinox*	*August, September, October*
4	*December Solstice*	*November, December, January*

Also, values of sunspot number (R_z) were used to group the study years into low solar activity (LSA) with $R_z < 20$, moderate solar activity (MSA) with $20 < R_z < 100$, high solar activity with $Rz > 100$, as shown in Table 2.

Table 2: The Sunspot number for three Solar Activity Epoch in the Solar Cycle.

S/N	Sunspot Number (R_z)	Solar Activity
1	$R_z > 100$	*High Solar Activity*
2	$100 \geq R_z \geq 20$	*Moderate Solar Activity*
3	$R_z < 20$	*Low Solar Activity*

To investigate the performance of the ionospheric models, the Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) were used. RMSE is calculated using equation 2 as given in [27], [30] and several studies.

$$RMSE = \sqrt{\sum_{i}^{N} \frac{(TECmodel_i - TECgps_i)^2}{N}} \quad (2)$$

where N is the number of hours.

The MAE was calculated using equation 3.

$$MAE = \frac{\sum_{i}^{n} [\![y_i - x_i]\!]}{n} \quad (3)$$

where y_i is the prediction, x_i true value and n is the total number of data points. Equation 3 have been used widely in the field of ionospheric research and was adopted by [19], [24], [31], [32] and many others ionospheric scientist.

For a better understanding of the variations in TEC in the Australian region, the Universal time (UT) was harmonized to Local time (LT) using equation 4.

$$LT = UT+7 \quad (4)$$

The years studied and their corresponding sunspot number are shown inTable 3.

Table 3: The table showing Years, Solar Cycle Phase and Sunspot number.

S/N	Years	Sunspot Number(R_z)
1	2011	55.6
2	2012	57.6
3	2013	64.7
4	2014	79.6
5	2015	69.9
6	2016	39.9
7	2017	21.8

3. Results and Discussion

3.1 Diurnal and Seasonal Variation in TEC

Fig. 1 shows the diurnal and seasonal variations in GPS-TEC, IRI-Plas 2017, IRI-2016 and NeQuick-2 models at DAV1 station for year 2011.

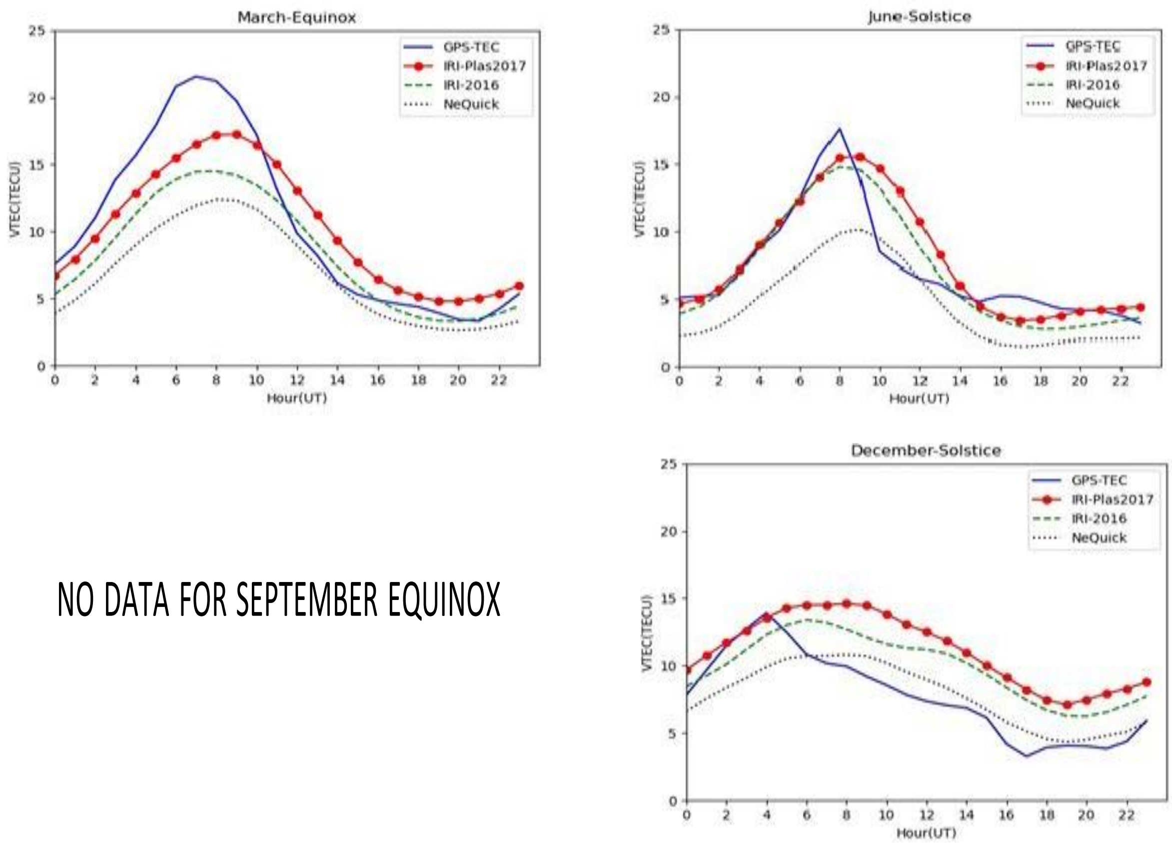

Fig. 1: Diurnal and Seasonal Variations in TEC at DAV1 for the year 2011.

During the March equinox, GPS-TEC values increase from 8 TECU during the early morning hours of the dayto a peak of ~ 21 TECU at 07:00UT, corresponding to 14:00LT and then decreases gradually to minimum value of ~ 3 TECU at 21:00UT (04:00LT). During June solstice, GPS-TEC values were slightly lower than March equinox at about the same time interval. During this season, GPS-TEC exhibits a double-humped feature called nighttime enhancement, which could be a result of the ionospheric plasma density diffusion that flows from the dip equator, leading to the formation of ionization anomaly that lasts for a few hours aftersunset [27, [29]. No data was recorded during the September equinox. During December solstice, the minimumvalue of TEC was exactly the same as observed in the other three seasons, while its peak value was ~ 14TECU at 04:00UT (11:00LT). The location of the GPS receiver in the polar region accounts for the ionizationof neutral molecules in the earth's upper atmosphere which have insignificant diurnal variations throughoutthe seasons, as a result of the low solar radiation [26]. The observed values of TEC in this study were generally lower than TEC values at the equatorial/low- and middle latitudes [20], as a result may have insignificant impact on the signal propagated through the ionosphere in the polar region [4], [33]. IRI-Plas 2017 increases gradually from 7 TECU during the early morning hours to a peak of 18 TECU at 10:00UT (05:00LT), and then gradually decreases to minimum value at 20:00UT (02:00LT) during March equinox. As a result of this, the electron density increases in the daytime hours when there is an enhancement of

EUV falling on the topside ionosphere [15]. Also, the plasmapheric contributions of TEC decrease as solar activity increases, as was investigated by [16]. During June solstice, maximum and minimum TEC values were slightly lower than March equinox, while December solstice recorded least magnitudes compared to the other three seasons, but with almost equal range of minimum value as March equinox [19]. IRI-Plas 2017 generally overestimates/underestimates TEC during all the seasons except during June solstice, where IRI-Plas 2017 and GPS-TEC values were nearly equal for the first few hours of the day. Also, the largest bottom-side contributions were observed during the December solstice season. IRI-2016 TEC value increases from ~ 6 TECU at 00:00UT (07:00LT), to a peak value of ~ 15 TEC at 7:00 UT (14:00LT), then gradually decreases to minimum value at 20:00UT (03:00LT) during March equinox. Similar variations were observed during the June solstice. During December solstice, IRI-2016 decreases by ~2 TECU. It can be observed that IRI-2016 model overestimated GPS-TEC during the night hours for all the seasons, except during March equinox where IRI-2016 and GPS-TEC values were about the same range. NeQuick-2 shows an increase from ~ 4 TECU at 00:00UT (07:00LT), to a peak value ~ 13 TECU at 8:00UT (15:00LT), before reducing to minimum value of ~3 TECU at 20:00 UT (02:00 LT). During June solstice, there was a reduction of ~ 2 TECU when compared to March equinox. December solstice recorded a slight increase and decrease in TEC. Generally, NeQuick-2 model shows the best performance in 2011, although there were slight overestimations from noon to night-time during December solstice.

Fig. 2 depicts the diurnal and seasonal variations in GPS-TEC, IRI-Plas 2017, IRI-2016 and NeQuick-2 models at DAV1 station for year 2012. During March equinox, GPS-TEC values increase from ~ 6 TECUat 00:00UT (07:00LT), to a peak value of ~ 19 TECU at 8:00UT (15:00LT), then decreases gradually to minimum value of ~ 4 TECU at 21:00UT (04:00LT). June solstice and the equinoxes recorded almost equal maximum and minimum values, while December solstice recorded slightly higher and lower maximum and minimum values than the other three seasons. This is because GPS-TEC values were highest during the month of December (winter anomaly). Winter anomaly is an ionospheric phenomenon peculiar to the equatorial and low latitudes. However, in the polar region, the month of December receives maximum solar radiation, which is referred to as the polar day (polar cap), while the month of June records the least solar radiation, because it is completely dark and is called the polar night [26]. These features could be attributed to the solar zenith angle. There was a great fluctuation in GPS-TEC at 3:00UT (10:00LT) and at 11:00UT (18:00LT) during December solstice. This could be as a result of the presence of polar cap in December solstice for year 2012, as a result of deposits of charged energetic particles, thereby causing the earth's magnetic field to have a coupling effect with the upper atmosphere, leading to the large variability in electron density [3]. IRI-2016 model is observed to increase from ~ 11 TECU at 00:00UT (07:00LT), to a peak value of ~ 28 TECU at 8:00UT (15:00LT), before reducing to minimum of ~6 TECU around 20:00UT (03:00LT) during March equinox. During the June solstice, the maximum value of TEC was ~ 8 TECU lower and the minimum value was ~ 2 TECU lower than what was recorded during March equinox. The peak values during the September solstice and June solstice were slightly lower, while the minimum value during September equinox was slightly lower, while December solstice was twice as high as March equinox. Generally, IRI-2016 model shows overestimation for most hours of the day during all seasons, except during December solstice where IRI-2016 overestimated GPS-TEC throughout the day. IRI-Plas 2017 model is observed to increase from ~ 9 TECU at 00:00UT (07:00LT), to a peak value of ~ 22 TECU at around 07:00UT (14:00LT), before reducing steeply to minimum value at 20:00UT (03:00LT) during March equinox season. June solstice and September equinox recorded a shortfall in TEC values within the same time interval, while December solstice recorded minimum TEC value ~ 5 TEC higher than March equinox, but with a peak value of ~ 4 TECU less than March equinox.

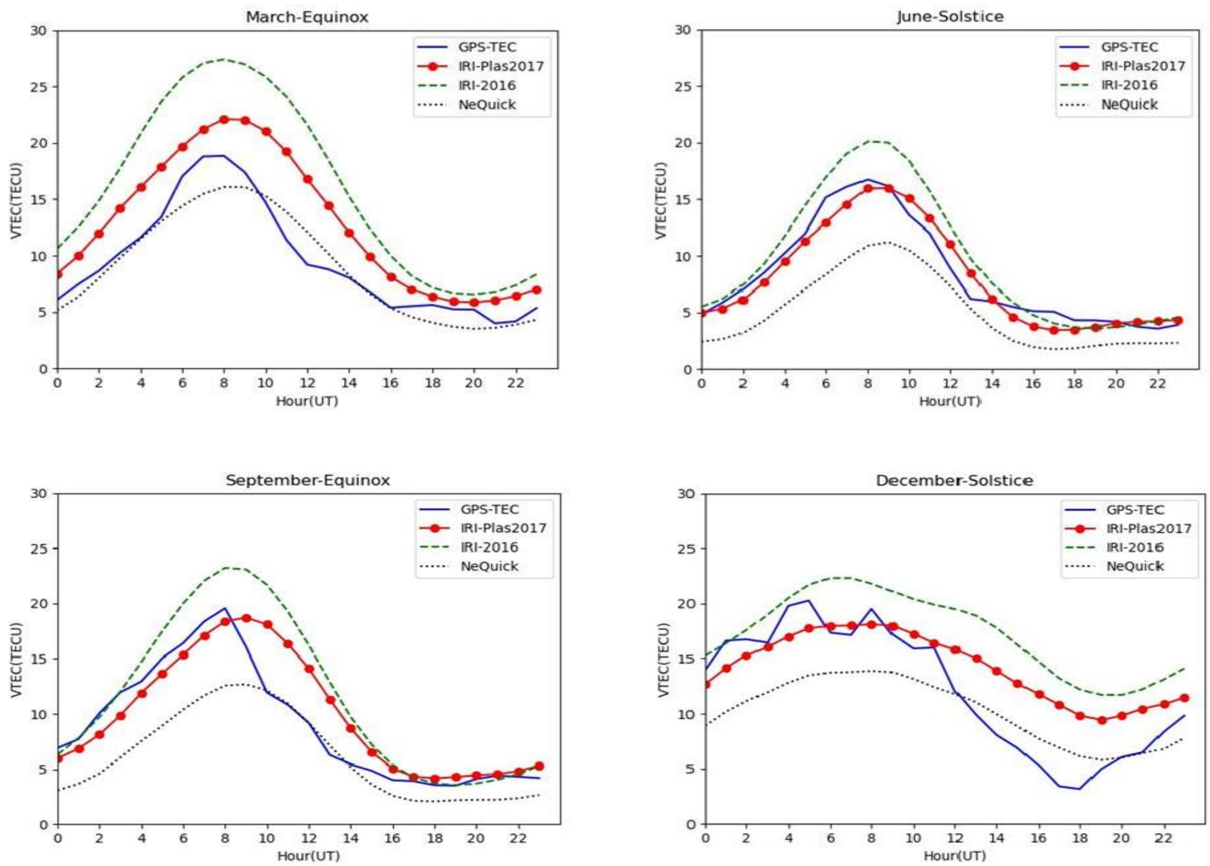

Fig. 2: Diurnal and Seasonal Variations in TEC at DAV1 for year 2012

Generally, IRI-Plas 2017 model overestimations were greater compared to IRI-2016 and NeQuick-2 models during the four seasons. Finally, NeQuick-2 model increases from 5 TECU at 00:00UT (07:00LT), to a maximum value of 16 TECU at 8:00UT (15:00LT), before decreasing gradually to a minimum value at 20:00UT (03:00LT) during March equinox. However, the September equinox and the solstices show similar variations. Generally, it can be observed from the plots that NeQuick-2 model prediction is most suitable for all the seasons in year 2012.

Fig. 3 indicates the diurnal and seasonal variations in GPS-TEC, IRI-Plas 2017, IRI-2016 and NeQuick-2 models at DAV1 station for year 2013. During the March equinox, GPS-TEC value increases from ~ 9 TECU at exactly 00:00UT (07:00LT), to a peak value of ~27 TECU 5:00UT (12:00LT) and then gradually decreases to minimum value at 19:00UT (02:00LT). During June solstice, maximum GPS-TEC value reduced to ~18 TECU, while the minimum value is almost in the same range as March equinox for some hours of the day. It was observed that GPS-TEC value fluctuates from post-noon to night-time period in the UT scale. These fluctuations may be attributed to high solar wind energy deposited from outer space, which persistently flows through the ionosphere between the months of March and June of the year, due to the effects of geomagnetic storms [22]. During September equinox, the peak value of GPS-TEC was slightly lower than March equinox, while the minimum value is nearly equal. During the December solstice, GPS-TECvalues rise from ~ 7 TECU at 00:00UT (07:00LT), to a peak value of ~ 26 TECU at 05:00UT (12:00LT), before decreasing to a double minimum value at 14:00UT (21:00LT) and 19:00UT (02:00LT). This double minimum GPS-TEC during December solstice could be attributed to the occurrence of sudden ionospheric disturbance (SID) that sometimes occurs towards night-time period, thereby causing a dramatic rise and fall in TEC value at that time [8]. IRI-2016 model rises from ~9 TECU at 00:00UT (07:00LT), to a maximum value of ~ 24 TECU at 8:00UT (15:00LT), and decreases steadily to its minimum value afterwards at 20:00UT (03:00LT) during March equinox.

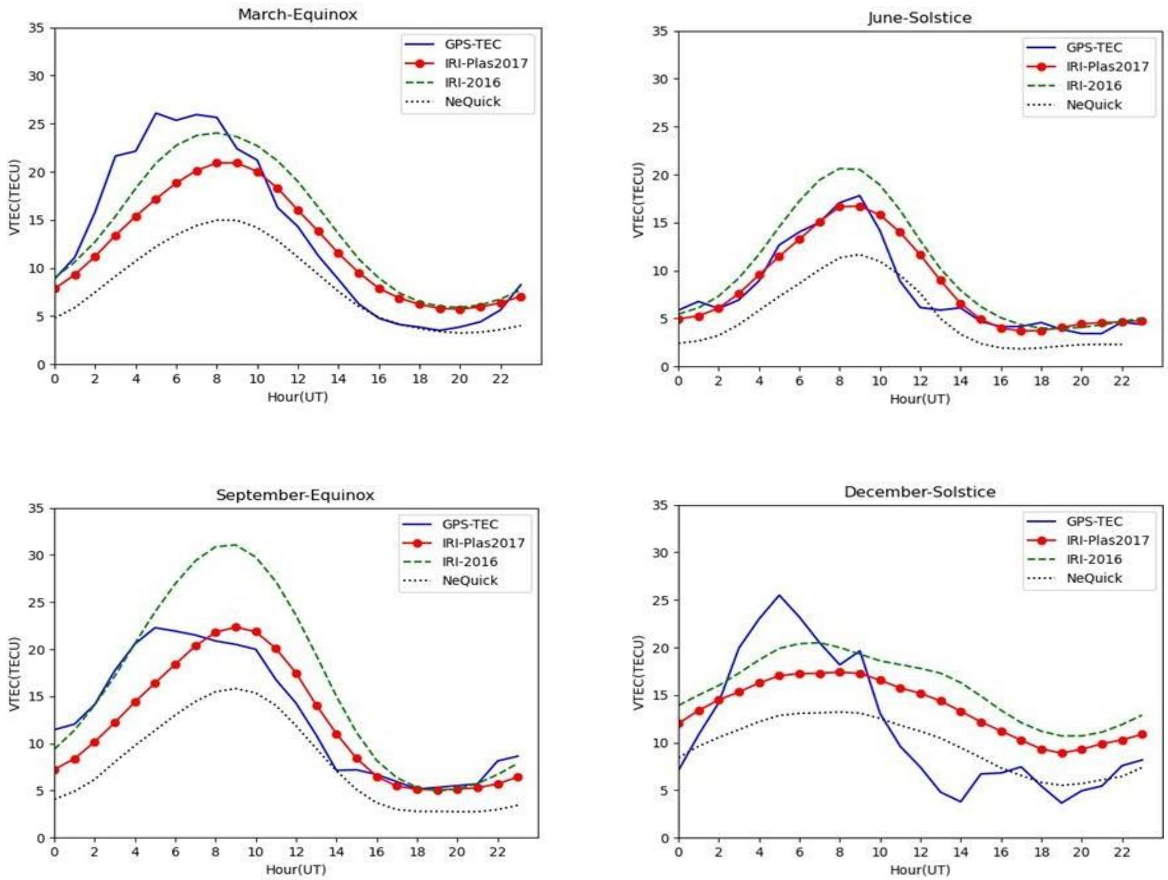

Fig. 3: Diurnal and Seasonal Variations in TEC at DAV1 for year 2013

During June solstice, the maximum and minimum values of TEC were ~3 TECU lower than in March equinox at about the same time interval. During September equinox and December solstice, the peak values were ~ 5 TECU higher and lower, respectively, while the minimum value was ~ 11 TECU for December solstice and was slightly higher compared to March equinox. Generally, IRI-2016 model prediction was about the worst, showing clear overestimation throughout the day for all the seasons. IRI-Plas 2017 increases from ~ 8 TECU at 00:00UT (07:00LT), to a maximum ~ 21 TECU at 8:00UT (15:00LT), before decreasing to minimum value at 20:00UT (03:00LT) during March equinox. During June solstice, the minimum value is almost the same, whereas the maximum value is slightly higher than in March equinox. During the December solstice, a reverse case was observed (i.e., a lower peak value and a slightly higher minimum value). Generally, IRI-Plas 2017 model prediction was about the best during this year, except for a few cases of underestimation during the early hours of the day and a few cases of overestimation during the later hours of the day. NeQuick-2 increases from ~ 5 TECU at 00:00UT (07:00LT), to peak value of ~ 15 TECU at 09:00UT (16:00LT), before decreasing to minimum value afterwards during March equinox. During June solstice, both the maximum and minimum values recordeda slight reduction in TEC values, while September equinox recorded a slightly higher maximum value and also depletion in minimum value when compared to March equinox. However, the reverse is the case during the December solstice. Generally, the NeQuick-2 model prediction was better than the other two models usedin this study.

Fig. 4 illustrates the diurnal and seasonal variations in GPS-TEC, IRI-Plas 2017, IRI-2016 and NeQuick-2 models at DAV1 station for year 2014. The plot shows GPS-TEC rising from ~ 15 TECU at 00:00UT (07:00LT), to a maximum value of ~ 43 TECU at 7:00UT (14:00LT), before decreasing steeply to minimum values afterwards during the March equinox. During June solstice, the maximum GPS-TEC value decreases gradually from ~ 20 TECU at 08:00UT (15:00LT), to minimum value in the later hours of the day. While the September equinox recorded a peak value of ~ 27 TECU about same time as June solstice, but steeply reduces to minimum values within the same time interval.

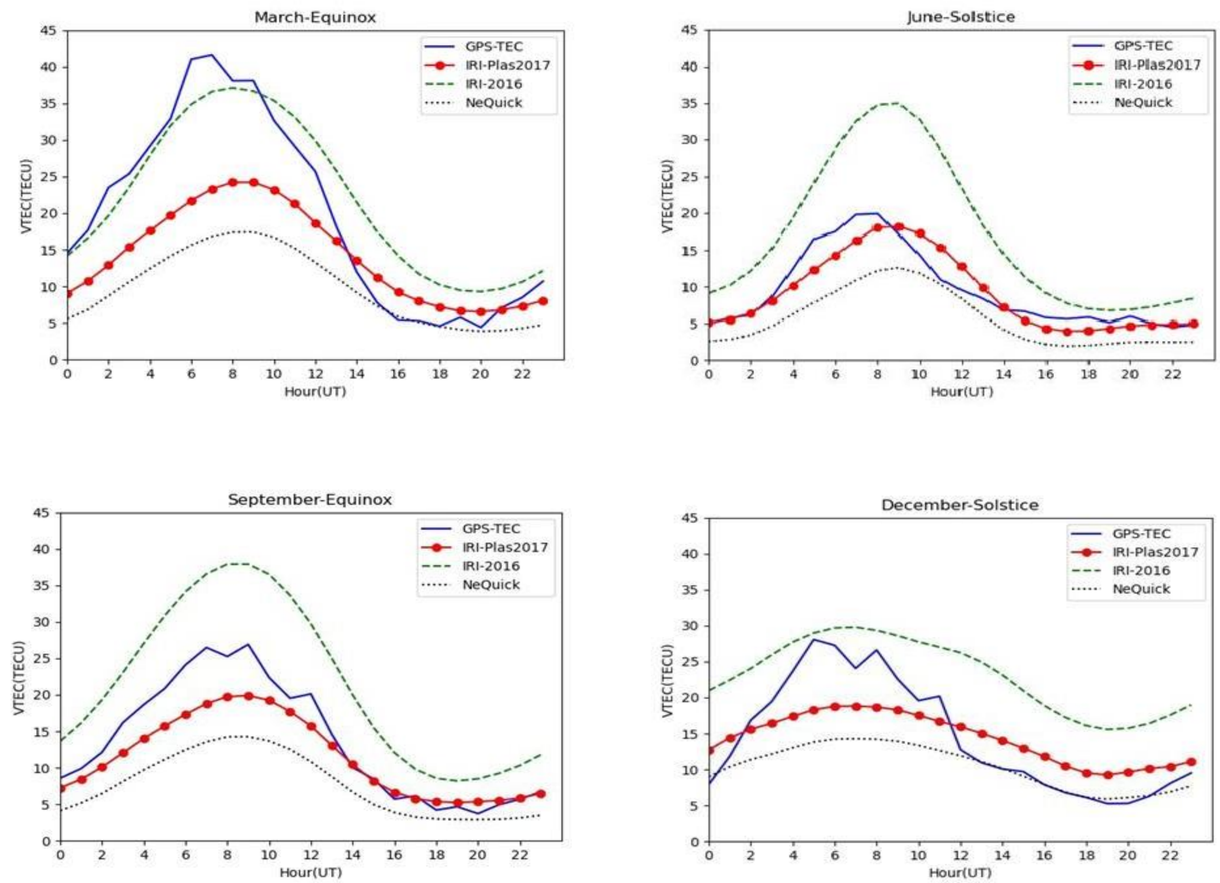

Fig. 4: Diurnal and Seasonal Variations in TEC at DAV1 for year 2014

An unusual decay in GPS-TEC occurred, referred to as local time noon bite-out. This delay observed by the GPS-TEC can be observed between 07:00UT (14:00LT) to 09:00UT (16:00LT). This phenomenon is an equatorial/ low latitude ionospheric phenomenon, as a result of the E× B drift in solar ionization. In Polar Regions, this phenomenon is hardly present. However, its rare manifestation may be due to the longitudinal location and hemispherical variations [35]. During December solstice, maximum GPS-TEC value was recorded to be ~ 28 TECU, while minimum GPS-TEC values was about the same range as the other seasons. IRI-2016 increases from ~ 15 TECU and reaches a maximum value of ~ 38 TECU, and then decreases steadily to minimum value ~ 9 TECU in the later hours of the day during March equinox. June solstice recorded slightly lower values, while September equinox values were slightly higher compared to March equinox. During the December solstice, the maximum value was lower while the minimum value was higher in the other three seasons. IRI-2016 model prediction was very poor, showing overestimations throughout the day during the four season of year 2014. IRI-Plas 2017 increases from ~ 9 TECU around midnight hours, to maximum value ~ 25 TECU during post-sunrise hours, and then decreases to minimum value ~7 TECU around the post-sunset hours during March equinox. June solstice and the September equinox recorded a decrease in maximum and minimum values compared to March equinox.

Fig. 5 illustrates the diurnal and seasonal variations in GPS-TEC, IRI-Plas 2017, IRI-2016 and NeQuick-2 models at DAV1 station for year 2015. During March equinox, GPS-TEC increases from ~ 18 TECU at 00:00UT (07:00LT), to maximum value ~ 35 TECU at 07:00UT (14:00LT), before decreasing to minimum 18:00UT (01:00LT). GPS-TEC is observed to show double peaks and nighttime enhancement during March equinox.

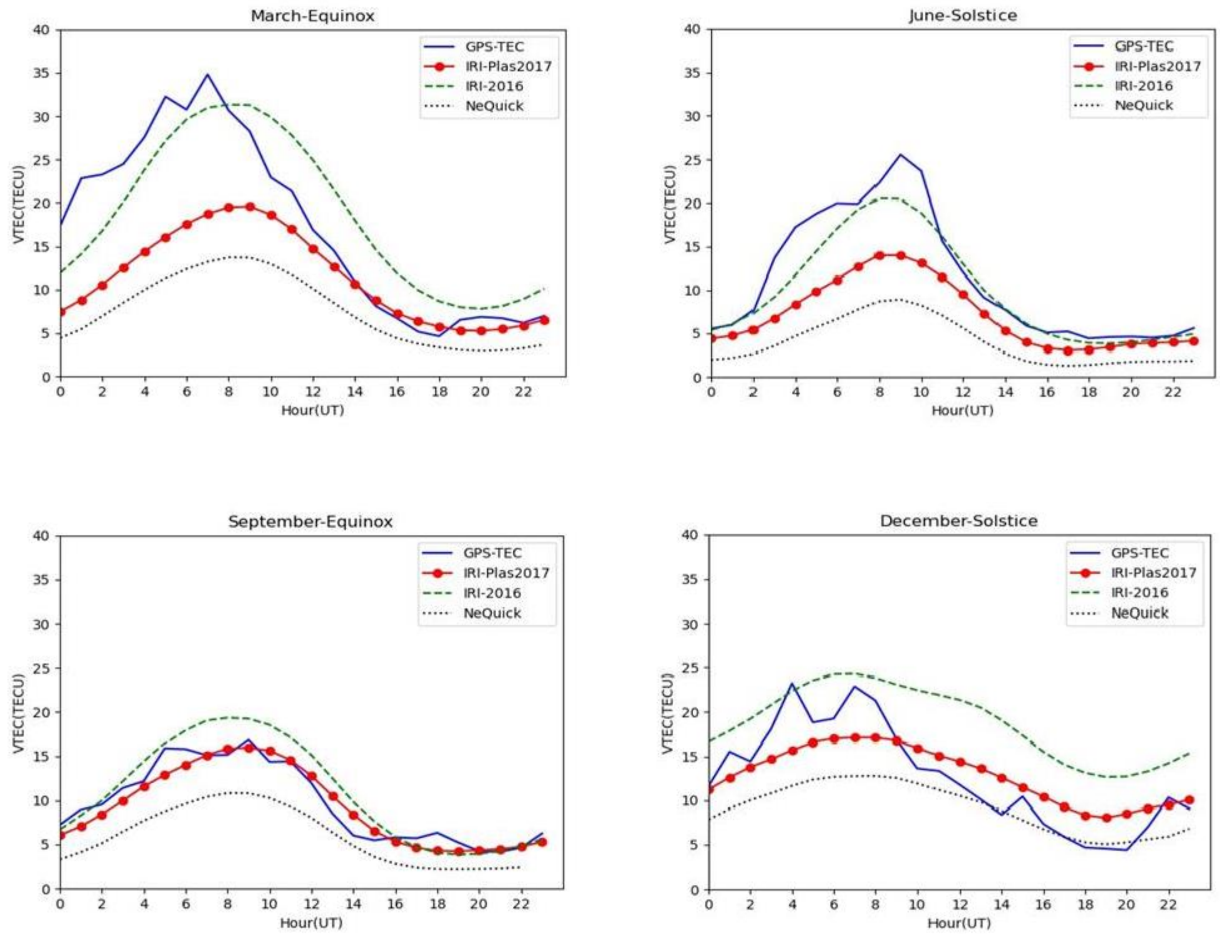

Fig. 5: Diurnal and Seasonal Variations in TEC at DAV1 for year 2015.

The double peaks and nighttime enhancement may trigger radio wave scintillations, which are rapid fluctuations in both amplitude and phase of radio wave signals propagating through the ionosphere [11]. During June solstice, the maximum TEC values reduced drastically, while the minimum values are about the same range as GPS-TEC, and September equinox had nearly similar variations as observed during March equinox. GPS-TEC values during June solstice exhibits LT night-time enhancement, which could be a result of the prolonged flow of ionospheric plasma from the equator to higher latitudes, which occurs during sunset and persists till the early hours of the following day [26],[34]. During the December solstice, reduction in the maximum and minimum GPS-TEC values were observed as compared to March equinox. Generally, TEC values exhibit equinoctial asymmetry, which is a phenomenon of unequal TEC magnitudes during the equinoxes. IRI-2016 model increases from ~ 13 TECU at 00:00UT (07:00LT), to a maximum value ~ 32 TECU at 8:00UT (15:00LT), before decreasing to minimum value ~ 8 TECU at 20:00UT (03:00LT) during March equinox. The June solstice and September equinox recorded a significantly lower value of TEC throughout the day, while the December solstice had its peak also at a lower value and its minimum value evenhigher during the same time interval compared to March equinox. IRI-2016 model prediction shows significant underestimation and overestimations during June solstice and September equinox. NeQuick-2 model increases from ~ 5 TECU at 00:00UT (07:00LT), to about 14 TECU at 9:00UT (16:00LT) and reduces to minimum value of ~ 3 TECU at 20:00UT (03:00LT). June solstice and September equinox showsdepletion in their maximum and minimum values, while December solstice recorded almost the same magnitude and slightly higher minimum value compared to March equinox. Generally, NeQuick-2 model has the best predicting capability during the four seasons for year 2015, although there were little underestimations recorded for some seasons. IRI-Plas 2017 model increases from ~ 8 TECU at 00:00UT (07:00LT), to peak value of ~ 20 TECU at 9:00UT (16:00LT) and decreases to minimum value ~ 5 TECU at20:00UT (03:00LT) during March equinox. During June solstice and September equinox, similar TEC variation was observed as IRI-2016 model, when compared to March equinox. December solstice, however, recorded slightly lower peak value and slightly higher minimum value compared to March equinox. Generally, the predicting capability of IRI-Plas 2017 was about the best during the four seasons for year 2015, except during the December solstice season, when its prediction was slightly poor.

Fig. 6 depicts the diurnal and seasonal variations in GPS-TEC, IRI-Plas 2017, IRI-2016 and NeQuick-2 models at DAV1 station for year 2016. In this year, GPS-TEC increases from ~ 9 TECU and increases to a first peak ~ 21 TECU at 04:00UT (11:00LT), and decreases suddenly to a value of ~ 18 TECU at 06:00UT (13:00LT), and increases afterwards to a second peak value ~ 22 TECU at 8:00 UT (15:00LT), before finally decreasing to minimum value of ~ 6 TECU at 21:00UT (04:00LT) during March equinox. Noon bite-out phenomenon was observed at 6:00 UT (13:00LT), which is the result of the enhancement of the eastward electric field over the geomagnetic equator flowing towards high latitudes [28],[35]. During June solstice, GPS-TEC values increase from ~ 5 TECU at 00:00UT (07:00LT), to a peak value of ~ 11 TECU at 7:00UT (14:00LT), before reducing to a minimum value of ~ 4 TECU at 21:00UT (04:00LT). September equinox andDecember solstice recorded higher maximum and minimum values than June solstice. Also, during December solstice, there was slight peak shifting to post-noon period with respect to the LT in the Australian region, which may be attributed to the December Polar Cap Day effects [26]. GPS-TEC was observed to show a haphazard (chaotic) or inconsistent fluctuation throughout the day during the four seasons in the year 2016. This may be due to the proximity of the GPS station to the Southern Antarctic Ocean in the southern hemisphere, resulting to high scintillations and multipath effects due to the Southern Atlantic Anomaly [25].The proximity of the GPS station to the Antarctic Ocean may also cause the height of the satellite transmitterto be greatly affected by cycle slip effects, which in turn causes inconsistency in TEC values (11). IRI-2016model is observed to increase from ~ 6 TECU at 00:00UT (07:00LT), to a peak value of ~ 15 TECU at 8:00UT (15:00LT), and then decreases to a minimum value of ~ 4 TECU at 20:00UT (03:00LT) during Marchequinox. June solstice, September equinox, and December solstice show the same trend as the same model in the previous year (2015). Generally, the prediction capability of IRI-2016 model shows few casesof underestimation throughout the day in some seasons. IRI-Plas 2017 shows an increase from ~ 7 TECUat 00:00UT (07:00LT), to a peak value ~ 17 TECU at 09:00UT (16:00LT) and decreases to a minimum value of ~ 5 TECU around 20:00UT (03:00LT) during March equinox. September equinox and the solstices show the same variations observed in 2015. Generally, the IRI-Plas 2017 reveals about the best prediction capability in this year, although with slight overestimations during the September equinox and December solstice. NeQuick-2 is observed to increase from ~ 4 TECU at 00:00UT (07:00LT), to a peak value ~ 12 TECU at 8:00UT (15:00LT), and finally decreases to minimum value of ~ 3 TECU around 20:00UT (03:00LT) during March equinox. Similar variations can be observed for the other three seasons. Generally, NeQuick-2 shows underestimation throughout the day for the four seasons.

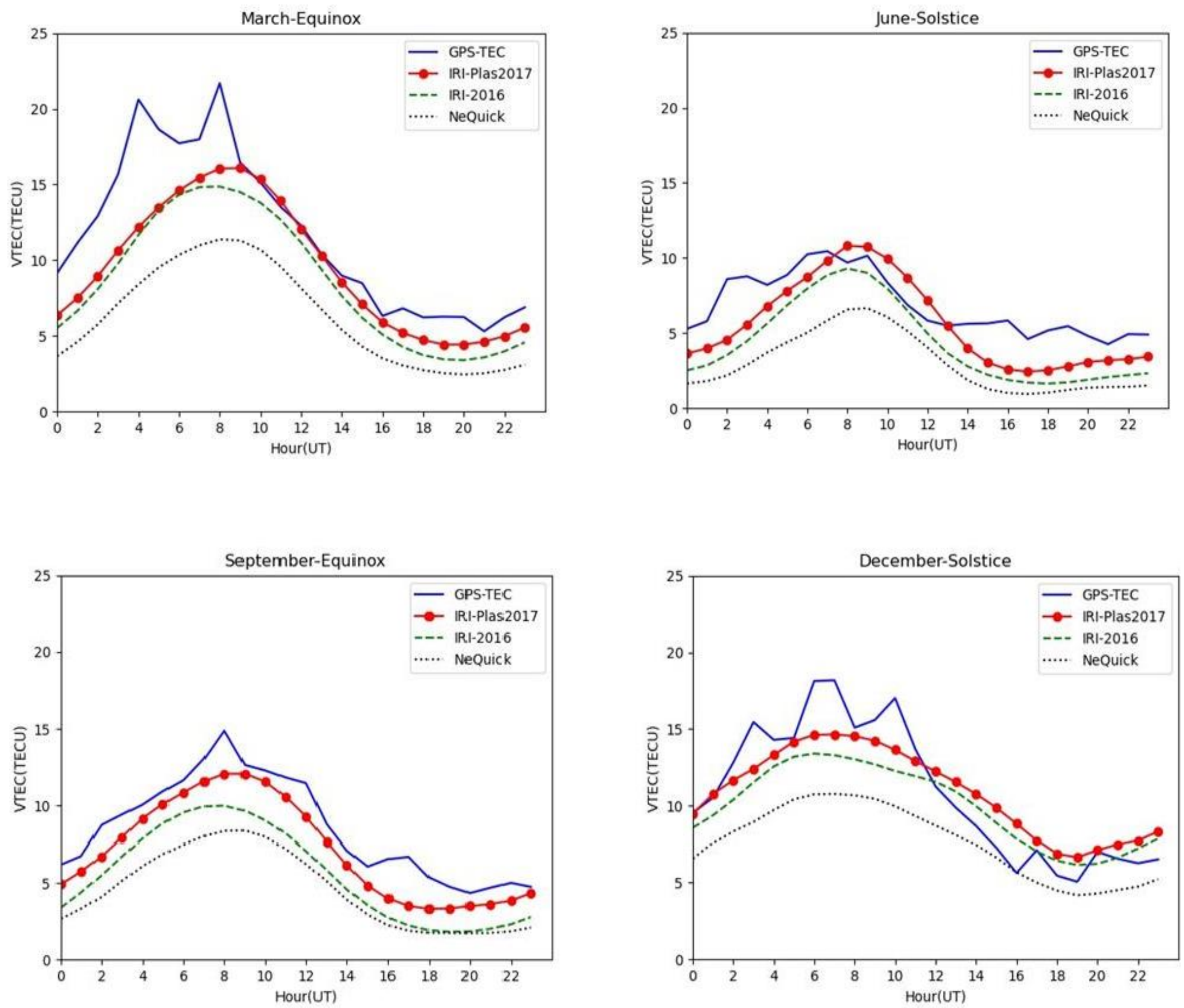

Fig. 6: Diurnal and Seasonal Variations in TEC at DAV1 for year 2016

Fig. 7 shows the diurnal and seasonal variations in GPS-TEC, IRI-Plas 2017, IRI-2016 and NeQuick-2 models at DAV1 station for year 2017. The year 2017 is a solar minimum year in solar cycle 24 with annual sunspot number of 22. During the March equinox, GPS-TEC values increase from ~ 9 TECU at 00:00UT (07:00LT), to a maximum value of ~ 20 TECU at 7:00UT (14:00LT), and then decreases to minimum value during post-sunset hours with respect to LT. The variations in TEC during September equinox and the solstices were similar with TEC variations during the same seasons in the previous year. IRI-2016 increases from ~ 4 TECU at 00:00UT (07:00LT), to maximum value of 10 TECU at 7:00UT (14:00LT), before finally decreasing to a minimum value of ~ 3 TECU around post-sunset hours with respect to LT during March equinox. During the June solstice and September equinox, the maximum and minimum values of TEC were lower thanMarch equinox, while December solstice TEC values were slightly higher than March equinox. Generally, IRI-2016 model shows underestimations throughout the days during the four seasons. IRI-Plas 2017 increases from ~ 5 TECU at 00:00UT (07:00LT), to peak value of ~ 14 TECU at 09:00UT (16:00LT), beforereducing to minimum value ~ 4 TECU afterward during March equinox. The same trend of variations wasalso observed during the September equinox and the solstices. IRI-Plas 2017 prediction capability was about the best when compared to the other two models used in this study. NeQuick-2 TEC variations were similar to IRI-2016 model, showing underestimations throughout the day during the four seasons. At this Australian GPS station, unevenness and recurrent patterns were observed in GPS-TEC due to occurrences of ionospheric irregularities [17]. Physical processes such as aurora display at low latitudes, geomagnetically induced currents (GICs), scintillation and solar energetic particle (SEP) events, etc., are also responsible for the ionospheric reaction to this recurrent geomagnetic activity.

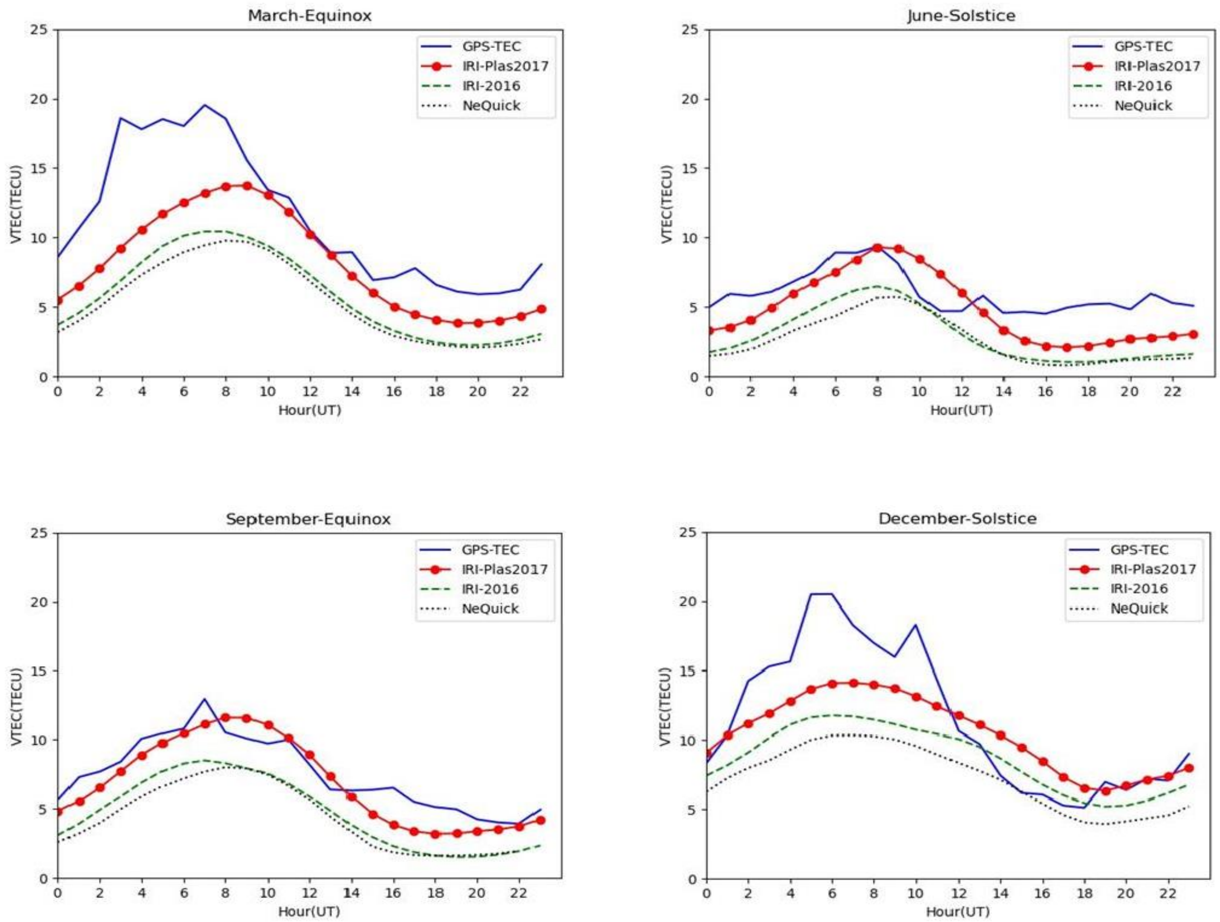

Fig. 7: Diurnal and Seasonal Variations in TEC at DAV1 for year 2017

3.2 Root Mean Square Error (RMSE)

From this research, the RMSE decreases with decreasing sunspot numbers. Invariably, the higher the solar activity, the lower the performance of the model, as reported by [21]. A typical metric for assessing the efficacy and effectiveness of a prediction model is the root mean square error (RMSE). Considering both the size and the direction of the mistakes, it calculates the average difference between projected and actual values. The average magnitude of prediction mistakes is measured by RMSE. A lower RMSE denotes smaller overall errors between the projected and actual values, which translates to improved prediction accuracy. RMSE is frequently used to evaluate the effectiveness of models in regression tasks across a variety of disciplines, including machine learning, statistics, and forecasting. The RMSE from January to December was denoted by 1 to 12, respectively.

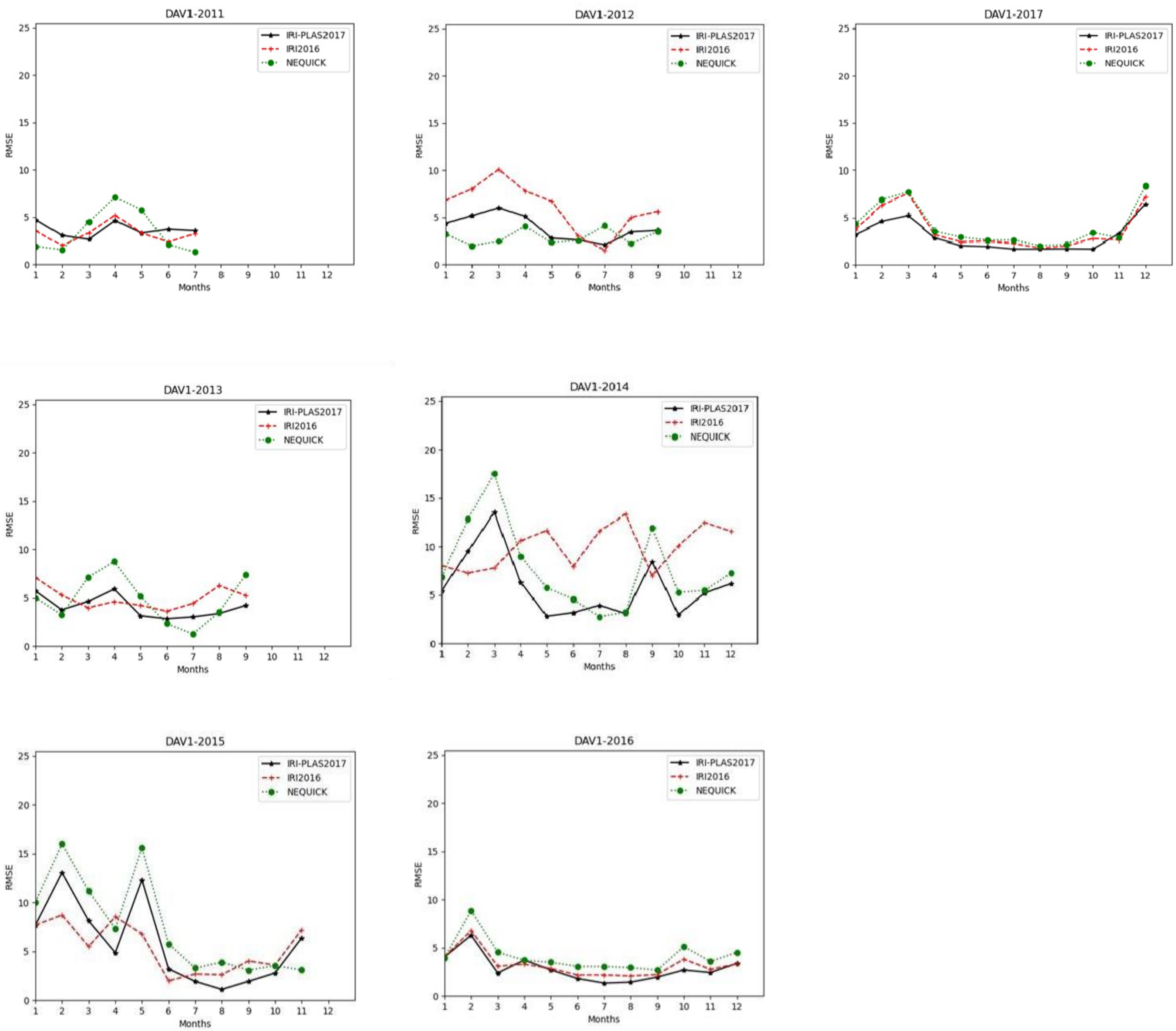

Fig. 8: Annual RMSE between GPS-TEC and IRI-Plas 2017, IRI-2016 and NeQuick-2 at DAV1 from 2011 – 2017.

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3.3 Mean Absolute Error (MAE)

In studies on meteorology, air quality, and climate, the root mean square error (RMSE) has been employed as a common statistical indicator to assess model performance. Another helpful metric that is frequently used in model evaluations is the mean absolute error (MAE) [9]. The MAE from January to December were denoted by 1 to 12, respectively.

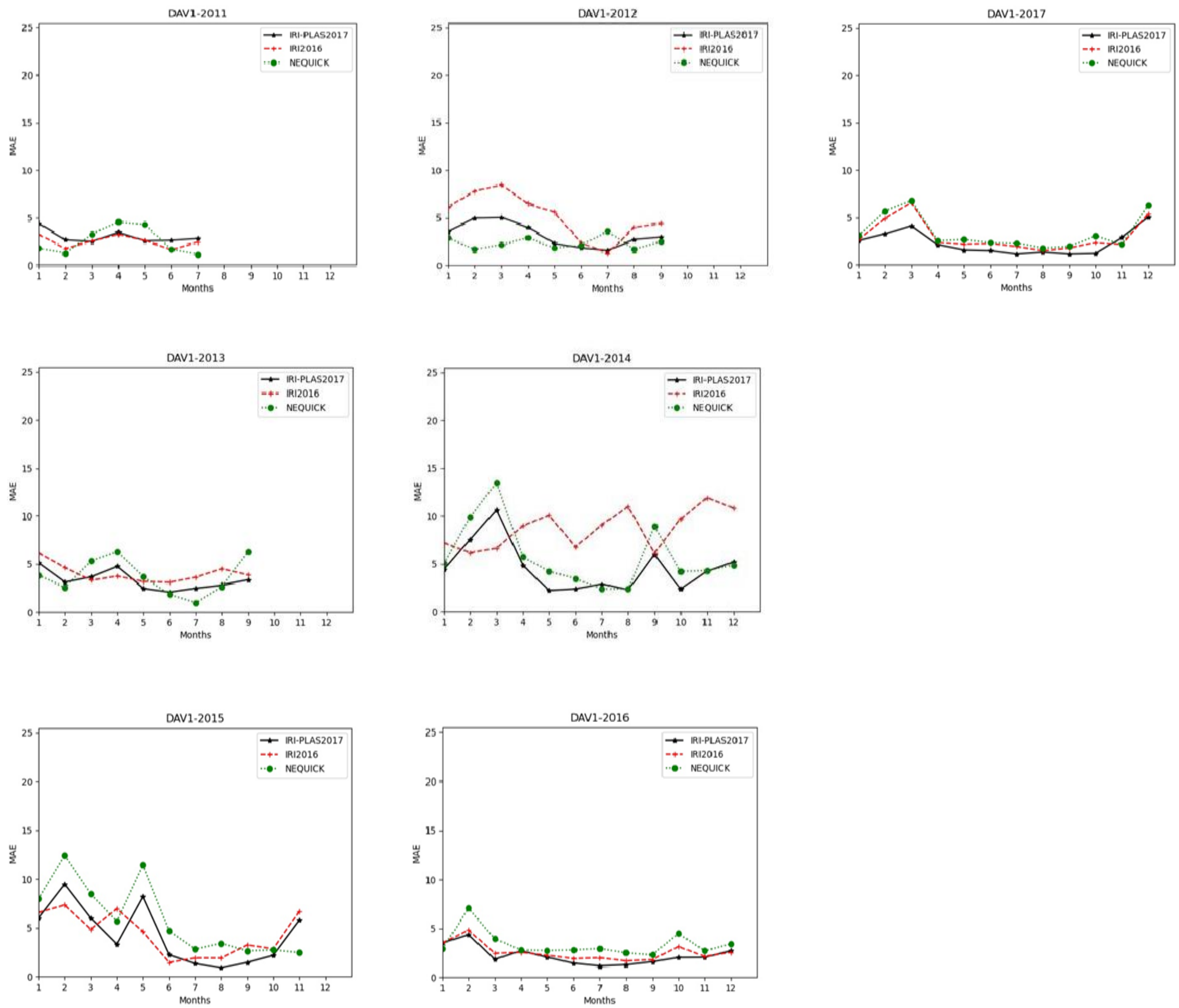

Fig. 9: Annual MAE between GPS-TEC and IRI-Plas 2017, IRI-2016 and NeQuick-2 at DAV1 from 2011 – 2017.

The mass plots in Figs. 8 and 9 show the annual RMSE and the annual MAE, respectively, at DAV1 for the year 2011 to 2017. It was observed that the annual prediction capability NeQuick-2 was better than IRI-Plas 2017 and IRI-2016 models during the years 2011 – 2013, showing a minimum value of 1.2 TECU during the month of July, while the IRI-Plas 2017 model had a fairly good prediction but had the worst performance in 2012 with a value of 5 TECU between February and March. For the years 2014 – 2017 solar cycle, IRI-Plas 2017 had about the best prediction over IRI-2016 and NeQuick-2 models, showing the lowest RMSE and MAE ~ 1.3 TECU and 1.5 TECU in the month of July, **respectively in 2017.** The lower the RMSE and MAE, the better the performance, and vice versa [9]. Therefore, the IRI-Plas2017 model had its lowest RMSE and MAE values during the years 2014 - 2017. The results here also showed that MAE was ~ 3 TECU less than RMSE for all the years used in this research, thereby making the MAE more effective as a metric for measuring the prediction capability of ionospheric models. Therefore, the MAE is an accurate and better metric than the RMSE, as reported in the work of [24] [27].

4. CONCLUSION

The diurnal and seasonal variations in GPS-TEC, IRI-Plas 2017, IRI-2016 and NeQuick-2models at an Australian station were investigated. The level of prediction of these ionospheric models from 2011 to 2017, which are years in solar cycle 2 was also ascertained. Predictions of ionospheric models need tobe examined/estimated in order to improve their level of efficiency when required. Results on diurnal variations show that the highest values of TEC (42 TECU) were observed from the GPS-TEC in this regionand were recorded at 05:00UT corresponding to 12:00LT, and at 09:00UT corresponding to 14:00LT hoursof the day in 2014, during the March equinox. The IRI-2016, IRI-Plas 2017, and NeQuick-2 models recordedtheir highest values of 38 TECU, 24 TECU and 17 TECU respectively, around 15:00LT of the day during March equinox of 2014. The seasonal variations show higher TEC values during the equinoxes than the solstices except for December solstice, which has almost equal magnitudes as March equinox and even higher than the September equinox. The analysis of the results show that IRI-Plas 2017 model had the best prediction capability, followed by IRI-2016, and the least is the NeQuick-2 throughout the study period withpercentage performance of 54.2%, 26.4%, 19.4% respectively. The RMSE and MAE which are widely used in the field of ionospheric physics were also employed in this study. However, the MAE recorded lower values as compared to the RMSE, although some of their values were very close, showing RMSE of ~3 TECU greater than the MAE in some months of the year. Tidal waves and ocean currents are the possible major contributing factors to the anomalous behavior of the GPS-TEC in the Australian region, which in turn may have affectedtheprediction of the ionospheric models during the study period.

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COMPETING INTERESTS

The authors declared that there are no conflicts of interest.

AUTHORS' CONTRIBUTIONS

Yusuf Kayode designed the study, performed the statistical analysis, Aghogho Ogwala wrote the protocol the draft of the manuscript. All other authors managed the literature searches and read and approved the final manuscript.

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