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PERFORMANCE OF IRI MODEL OVER TWO MID-LATITUDE STATIONS IN THE AFRICAN SECTOR

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Abstract

The use of Global Positioning System (GPS) for communication and navigation systems in Africa has gain a lot of paste in recent years. Modelling how the GPS signal behaves over this region to carter for forecasting and migration as also become very important. This study examined the seasonal variation of Total Electron Content (TEC) and also checks the performance of the three options in IRI-2012 model to predict TEC for the year 2010 (a year of low solar activity). TEC over two mid-latitude stations (RABT 34° N 6.85° W and SUTH 32.38° S 20.81° E) one on each hemisphere, north and south, in the African sector were considered. The results showed TEC exhibited diurnal and seasonal variations. TEC values attain minimum during the pre-sunrise (0500 – 0600 LT), maximum values were observed just after noon (1300 – 1500 LT) and thereafter decreases till mid night. The seasons also exhibited daytime depression before noon and after noon for northern and southern hemispheres respectively. The model estimate replicated the morphology of TEC, this is evidence in the correlation coefficients. The model options generally underestimated GPS-derived TEC during the pre-sunrise, overestimated it at daytime and later underestimated TEC later in the day. The model exhibited different performance for the two stations over the seasons considered. The overall best option could not be ascertained at this region as compared to other works done for the other regions; equatorial and low latitude regions.

Keywords: TEC, GPS, IRI-2012.

1.0 Introduction

The use of Global Positioning System (GPS) cannot be over emphasized in this modern age of satellite communication and navigation system. The GPS signals transmitter on board satellite under goes signals degradation. The GPS signals are affected by variations in the earth upper atmosphere (ionosphere). These variations are caused by the presence of electron density in the medium. This in turn affects the communication, navigation and positioning capability of the GPS satellite. One of the important parameter in the ionosphere that affect GPS signal is the Total Electron Content (TEC). TEC is simply defined as the total number of free electrons present in a column of 1 m^2 cross-section along the line of sight path from the satellite to the receiver and it is measured in TEC unit (1 TEC unit = 10^{16} electrons per square meter). The knowledge of TEC morphology helps in systems design against signal degradation. Availability and Installation of GPS-receivers across the African continent has made the study of ionospheric TEC easier [1 – 6]. GPS data have a better accuracy in both time and space, therefore, it is widely used for ground based ionospheric studies [7 – 12]. TEC in the mid-latitude is subjected to day-to-day and seasonal variability, this poses as a problem for ionospheric models [13, 14]. There are several models for ionospheric studies; University Global Assimilation of Ionospheric Measurements (USU-GAIM) [15], Nequick (Neq) [16], semi-empirical low-latitude ionospheric model (SLIM) [17], and International Reference Ionosphere (IRI) [18, 19]. The most widely used model is the IRI, this model is based solely on the use of experimental data available from both ground and space sources. The IRI model is constantly updated by the scientific community committee on space research (COSPAR) and international union of radio science (URSI) [20 – 22]. Further description of the IRI model can be found in [23].

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The validation of the IRI model with the measured GPS data for mid-latitude regions is important; this is due to its growing applications in various communication and navigation systems for both military and civilian use. Many works as been done in the area of validation of IRI models with various latitudinal regions of the earth [24 – 30]. The performance of IRI was very high irrespective of the season in northern mid-latitude; this was attributed to higher density of data available in that region as reported in [31]. In the African sector, most works reported the performance of the model for equatorial region [22, 27, 32 – 36]. However, their works showed that IRI-2012 either under-estimated or over-estimated the observed values of TEC at a particular time of the day, season or solar activity.

Therefore, in this study, we present the seasonal variation of TEC at two mid-latitude stations (RABT 34° N 6.8° W and SUTH 32.38° S 20.81° E) one on each hemisphere, north and south, in the African sector. The performance of the three options in IRI-2012 model was also compared with measured GPS-TEC.

2.0 Data and Method of Analysis

Slant total electron content (STEC) recorded by the GPS receiver located at two mid-latitude stations in the African sector, RABT and SUTH was used in obtaining vertical total electron content (VTEC). Data for the year 2010 were utilized. This is a year with the Zurich Sunspot number, Rz = 16, which represents a year of low solar activity, see Figure 1.

The GPS data, which are in RINEX format, is accessed on UNVACO website: http://facility.unavco.org/data/-dai2/app/dai2.html. Ionospheric shell height of 350 km was used for the analysis (thin shell approximation). STEC obtained from the GPS receivers are uncorrected and are converted to VTEC. The corrections were implemented by using the GPS-TEC analysis application software developed at the Institute for Scientific Research, Boston College USA [37]. The average hourly-monthly values obtained from the 30 sec values were used to investigate the diurnal variations. The seasonal variations in TEC were investigated by grouping the months in a year to different seasons. They are namely: March equinox (February, March and April); September equinox (August, September and October); June solstice (May, June and July); and December solstice (November, December and January).

In addition to GPS derived TEC, TEC values from IRI-2012 model (which comprises of three options namely, IRI-01Corr, IRI-2001 and NeQuick), will be validated with the TEC values derived from the GPS.

TEC values predicted by the three options in the IRI-2012 model were generated from http://omniweb.gsfc.nasa.gov/vitmo/iri2012_vitmo.html. In order to study the performance of the model, TEC data during the international quiet days of each month were average over the three representative months of each season. By using equation (1) – (3), percentage deviation, Coefficient of Determination (r^2) and Root Mean Square Error (RMSE) of each of the options from the observed values were obtained respectively.

$$\Delta TEC = \left(\frac{TEC_{gps} - TEC_{IRI}}{TEC_{gps}} \times 100 \right). \quad (1)$$

$$r^2 = \frac{\left(\sum_i^n \left(TEC_{o_i} - \overline{TEC}\right)\left(TEC_{P_i} - \overline{TEC_P}\right) \right)^2}{\sum_i^n \left(TEC_{o_i} - TEC\right)^2 \times \sum_i^n \left(TEC_{P_i} - \overline{TEC_P}\right)^2}. \quad (2)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_i^n \left(TEC_{P_i} - TEC_{o_i}\right)^2}. \quad (3)$$

where, ΔTEC is percentage deviation in TEC, TEC_{gps} is the measured TEC by GPS, TEC_{IRI} is the modelled TEC. TEC_{o_i} is the measured TEC value from the GPS station and TEC_{P_i} is the predicted value from the IRI-2012 model, *i* is a specific observation and *n* is the number of observation.

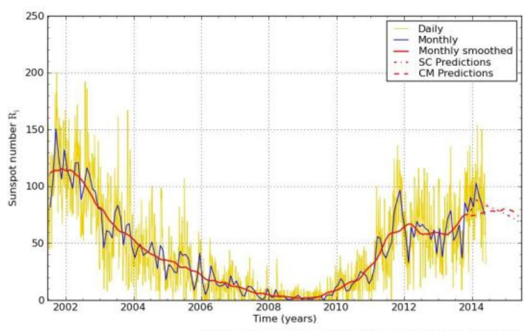

Figure 1: The international Sunspot Number Ri from 2002 to 2014 and forecast.

3.0 Results and Discussion

3.1 Seasonal Variation

Figure 2 (a – b) shows the monthly-hourly averages for the months that represent the four seasons, for the two stations, RABT and SUTH. The morphology of TEC follows a general trend irrespective of the season. TEC rises sharply from its minimum, which occurred around 05:00 LT- 06:00 LT, during sunrise period. The daytime peak values are attained between 12:00 LT to 15:00 LT for different seasons and later decreases after sunset to attain its minimum just before sunrise. The result showed that the diurnal variation peak is not symmetrical about noon. This is a deviation from a typical Chapman variation, which expects the peak to be symmetrical about noon. For the station in the northern hemisphere Figure 2a, the solstice peak values are lower than the equinoctial value. December solstice recorded the least peak TEC value 14.0 TECU, while for June solstice had ~16.0 TECU. The minimum pre-sunrise values range from about 3.0 to 8.0 TECU around 06:00 LT, except for December solstice, which recorded around 05:00 LT. there was a sharp rise from sunrise around 07:00 LT to 09:00 LT for both March equinox and June solstice. September equinox and December solstice had a relatively steady increase in TEC values during this period. The equinoxes are not symmetrical, March equinox being higher (~21.0 TECU) than September equinox (~16.0 TECU). Figure 2b represents the seasonal variation for the station in the Southern hemisphere. In this hemisphere the seasons are grouped such that, December solstice represent summer months, June solstice stands for winter months, then the equinoxes, that is March and September equinox. Form Figure 2b March equinox and December solstice recorded the highest TEC values, ~19 TECU each at around 14:00 LT and 15:00 LT. June solstice (southern winter) daytime peak value (~18 TECU, at 13:00 LT) was higher (winter anomaly) than September equinox peak value (~17 TECU, at 12:00 LT). This was different from earlier study in [12, 22] for stations in the southern hemisphere at low latitude. Their studies showed that June solstice recorded the lowest daytime maximum TEC values. There was a steady decrease in TEC after post-noon peak until the pre-sunrise period. The diurnal variability of TEC had been shown to been influenced by many parameters like extreme ultraviolet radiation (EUV) flux, geomagnetic activity, Equatorial ElectroJet (EEJ) strength and local atmospheric conditions in the thermosphere [25]. The minimum pre-dawn TEC observed for the two stations at both hemispheres for the entire seasons is in line with other studies [38 – 41]. They suggested that the weak variability of TEC during the pre-sunrise hours can be attributed to recombination that takes place at night, which also extend to the early hours of the day.

The steady rise of TEC during the sunrise period, from about 07:00 – 11:00 LT can be associated to the EUV, photo-ionization production starts to build up the concentration of plasma which last throughout the daytime, [42, 43]. The sharp decrease in TEC after the daytime maximum can also be attributed to a decrease in the intensity of EUV incident on the Earth's upper atmosphere around this time. This on the other hand leads to a reduction in the level of photo-ionization, since EUV is the major source of ionization during this period. The higher values of TEC at the equinox for RABT as compared to solstice can be attributed to a combine effect of magnetic field geometry and solar zenith angle, which is an important factor in the production of ionisation. The seasonal effect can also be associated with the location of sub-solar point in relation to magnetic equator [41, 44 – 46]. For the southern hemisphere, December solstice TEC value being the highest as compared to other seasons is expected. The sub-solar point at this time of the year lies around 23.5^{o} S, this makes the Earth's axis to be tilted towards the sun at this hemisphere, thus influencing the production rate of ionisation (Photoionization).

From Figure 2(a – b) there is the occurrence of daytime depression (bite out) during December solstice for both stations. The bite outs were recorded around 13:00 LT and 12:00 LT for RABT and SUTH respectively. The initial peak value before the bite out range from (~12 – 17 TECU) and the second peak value range from ~14 – 20 TECU. It was observed that the peak values before the bite out are lower than the second peaks after the bite out. The bite out is a common feature that occurs in the equatorial ionosphere, as reported in [12, 47, 48]. This feature is also observed in this study for mid-latitude stations at the two hemispheres. The daytime depression can be attributed to chemical losses due to fountain effect in the daytime. These chemical losses are increased by both the downward driven motion of eastward and pole-ward neutral wind moving away the fountain effect at noon until afternoon [39, 49, 50].

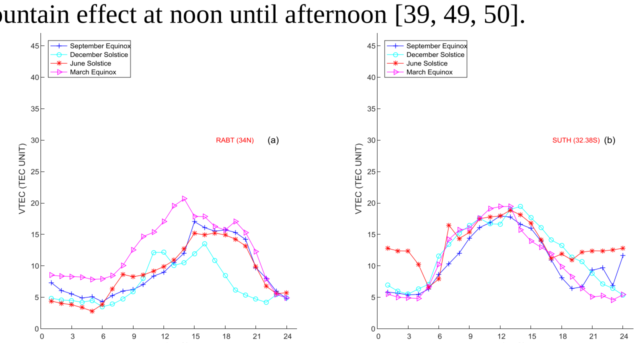

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Figure 2: Seasonal variation of TEC for the two stations in (a) RABT, Northern hemisphere (b) SUTH, Southern hemisphere.

The equinoxcial asymmetry was examined using the average sunspot number (SSN) for the year 2010. Figure 3 represent average sunspot number (SSN). The SSN shows the level of the sun activity during a particular period. The SSN was higher in March equinox (21.65 SSN) as compared to September equinox (19.17 SSN). This explains the higher maximum daytime value recorded in March as compared to September equinox.

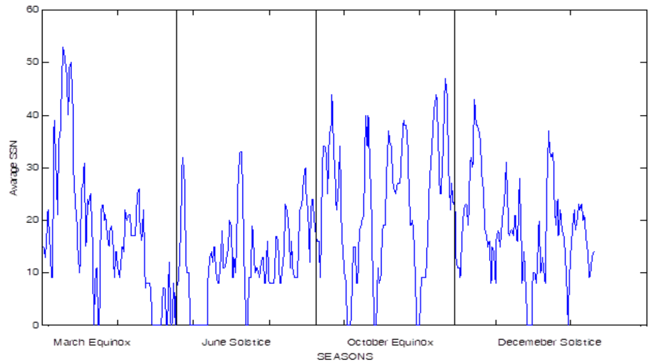

Figure 3: Average sunspot for the year 2010.

3.2 Prediction of the Seasonal Variation by IRI-2012

Figures 4 – 7 (a – b) show the comparison of the seasonal GPS derived TEC values for the two stations with the three options of the IRI-2012 TEC prediction model; IRI-01Corr, IRI-2001 and NeQuick during March equinox (Fig. 4a – b), September equinox (Fig. 5a – b), December solstice (Fig. 6a – b) and June solstice (Fig. 7a – b). Results for the three options showed that the model reproduced the morphology in the GPS derived TEC for both stations. However, the options performed different at predicting the GPS derived TEC during the seasons. Generally, the three options predicted TEC in an intermittent fashion in this study (mid-latitude region). The studies in [12, 22] showed that, for equatorial and low latitude regions, IRI-2001 had the greatest error in prediction irrespective of the seasons. While NeQuick option did predict TEC values quite well and IRI-01 Corr exhibited intermediate performance across the seasons. Table 1 (a – b) shows the correlation coefficients of GPS derived TEC to the predicted options in the model. Predicted TEC and GPS TEC are highly correlated for the two stations, but with an exception of two seasons in September equinox (NeQuick option) and December solstice (IRI-01 Corr and IRI-2001). This information is not in itself sufficient to draw conclusions on the performance of the models, as revealed by Figs 4 – 7 (a – b). For March equinox, Fig 4 (a – b), the model options underestimated the GPS TEC values during the pre-sunrise period till early sunrise time ~07:00 LT. At about 0800 LT, two options, IRI-2001 and IRI-01 Corr overestimated TEC values till 1600 LT, thereafter, it underestimated the GPS TEC values. For the same station, NeQuick option predicted the values quite well till about noon and later underestimated the values. Likewise, for the southern hemisphere station, SUTH as shown in Fig 4b, IRI-2001 predicted TEC values well from around 0700 LT – 0900 LT, thereafter overestimated it throughout the day. Similar trend was observed for IRI-01 Corr while NeQuick option underestimated TEC values throughout the day.

During September equinox Fig 5 (a – b), for RABT station Fig 5a shows that the prediction by the model options were close though some values were underestimated. It can be seen that, from sunrise to about 1700 LT the options overestimated TEC values and later around 1800 LT, the options underestimated the TEC values. Whereas, for the SUTH station Fig 5b shows that all options underestimated TEC values throughout the day.

During December solstice Fig 6 (a – b), for RABT station, IRI-2001 overestimated TEC values around 0100 LT – 0600 LT, NeQuick underestimated TEC values while IRI-01 Corr prediction were very close during the same period. From sunrise 0700 LT to 2300 LT the options overestimated TEC values throughout except for NeQuick which later underestimated the TEC values around 1600 LT. For SUTH station, the options underestimated TEC values all through the day, except NeQuick that overestimated for about two hours (1100 – 1200 LT). Moreover, June solstice Fig 7 (a – b) behaved similarly to December solstice for both stations. The exception to this is that, IRI-2001 predicted TEC values were very close to the observed TEC values from 0900 LT – 1700 LT.

Table 1: Correlation coefficients between GPS vTEC values and the IRI vTEC values for (a) Northern hemisphere and (b) Southern hemisphere

(a)		**RABT**	
SEASONS	NeQuick	IRI01-Corr	IRI-2001
March Equinox	0.74	0.63	0.64
September Equinox	0.38	0.53	0.54
June Solstices	0.61	0.81	0.82
December Solstices	0.71	0.42	0.43
(b)		**SUTH**	
SEASONS	NeQuick	IRI01-Corr	IRI-2001
March Equinox	0.91	0.89	0.88
September Equinox	0.85	0.89	0.89
June Solstices	0.97	0.97	0.97
December Solstices	0.73	0.63	0.63

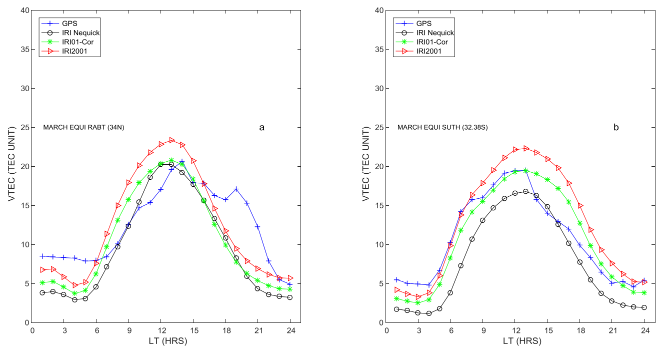

Figure 4: Comparison of GPS-vTEC and IRI-2012 for March equinox at (a) RABT (b) SUTH.

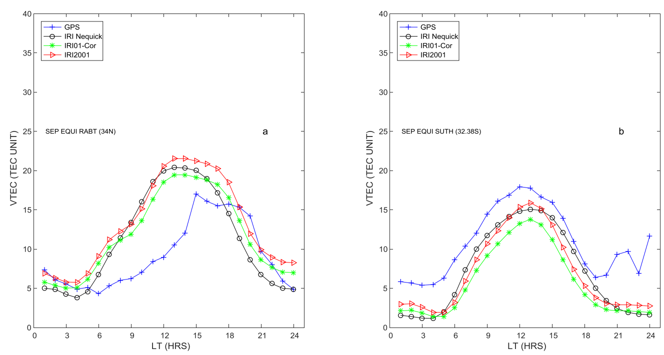

Figure 5: Comparison of GPS-vTEC and IRI-2012 for September equinox at (a) RABT (b) SUTH.

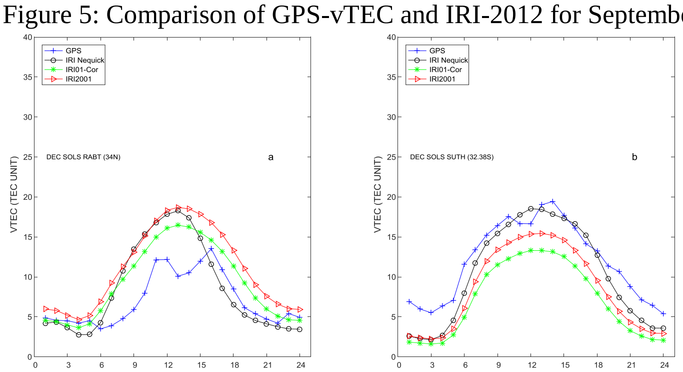

Figure 6: Comparison of GPS-vTEC and IRI-2012 for December solstice at (a) RABT (b) SUTH.

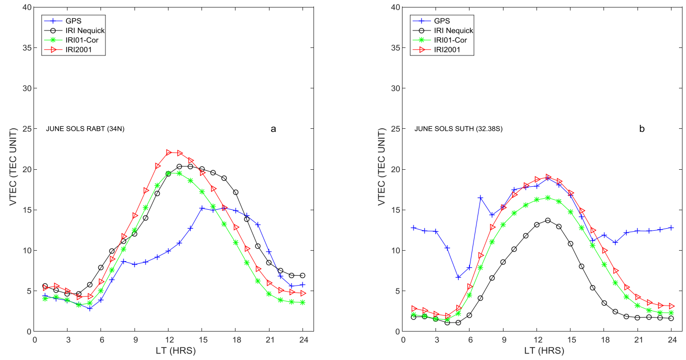

Figure 7: Comparison of GPS-vTEC and IRI-2012 for June solstice at (a) RABT (b) SUTH.

Fig 8 – 11 (a – b) show the percentage deviation of GPS derived TEC from the model options for the two stations, covering the entire seasons. The plot for all seasons reveals that each option performed than other for different seasons. The least percentage deviation where alternated for different seasons and station location. NeQuick option had the least percentage deviation for the following seasons September equinox (10%) and December solstice (2.0%) for SUTH. IRI-01 Corr performed better in March equinox (0.02 ~ 2.10%) for both stations, September equinox (9%), and June solstice (3%) for RABT. However, the least percentage deviation was recorded for IRI-2001 option in March equinox (3.40%) and June solstice (0.62%) for SUTH. The behaviour of the model for this study was different from an earlier study in [22] for equatorial stations in Africa sector. They observed that irrespective of the season, NeQuick option of the model had the least percentage deviation followed by IRI-01 Corr with IRI-2001 recording the highest percentage deviation.

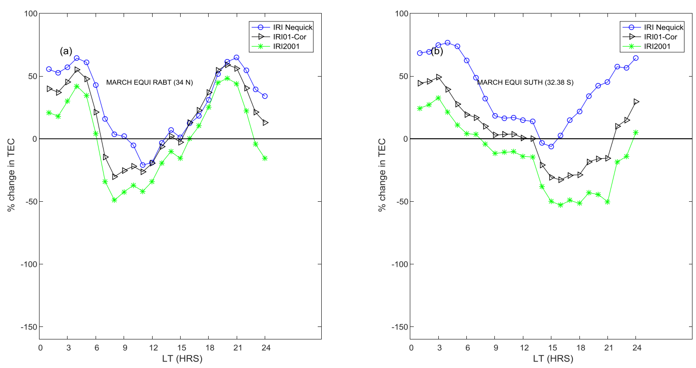

Figure 8: Percentage difference between GPS-vTEC and IRI-2012 estimation for March equinox at (a) RABT (b) SUTH.

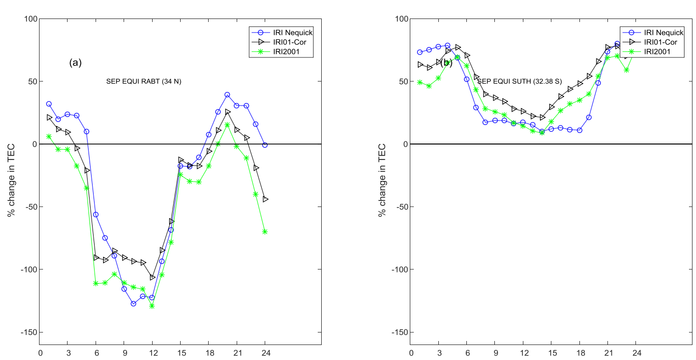

Figure 9: Percentage difference between GPS-vTEC and IRI-2012 estimation for September equinox at (a) RABT (b) SUTH.

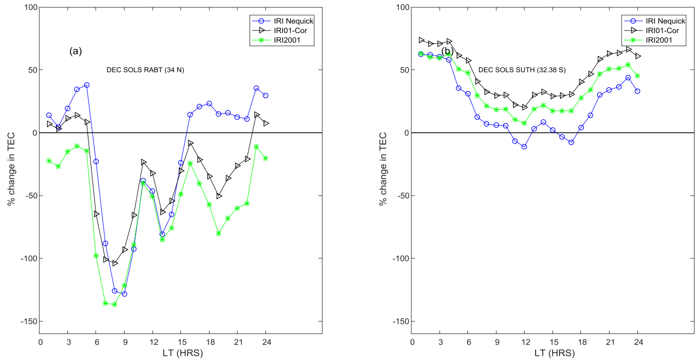

Figure 10: Percentage difference between GPS-vTEC and IRI-2012 estimation for December solstice at (a) RABT (b) SUTH.

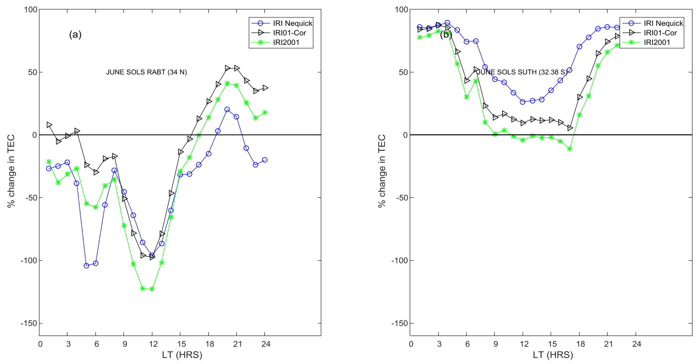

Figure 11: Percentage difference between GPS-vTEC and IRI-2012 estimation for June solstice at (a) RABT (b) SUTH.

Table 2 shows the root mean square error (RMSE). This is a measure of how close the model prediction data are to the GPS derived data. A smaller value indicates smaller error spread in the model. From Table 2, the best performing model option for March equinox is IRI-2001 (4.01) and IRI-01 Corr (2.16) for RABT and SUTH respectively. While in September equinox, the performance was interchanged for the two stations. That is IRI-01 Corr (4.46) and IRI-2001 (4.13) for RABT and SUTH respectively. During June solstice, IRI-01 Corr (3.19) performed best in RABT and NeQuick (2.34) was the overall best for SUTH. For December solstice, NeQuick (4.42) predicted GPS TEC values best for RABT while IRI-2001(5.88) did the prediction better than the other options for SUTH.

The underestimation by NeQuick and IRI-01 Corr during the early hours (01:00 – 07:00 LT) observed in this work can be attributed to the profile shape in the IRI model and upper integration heights (1500 km) of the model algorithm used. The profile shape in the IRI model was observed to be the cause of the deviation as reported in [20]. The underestimation could be because of N_mF_2 or shape of the electron density profile or both are not well predicted by the IRI model as suggested in [33]. The deviation during the early hours as also been reported by other works at the equatorial and low latitudes [22, 28, 32, 33, 51].

Table 2: Root Mean Square Error (RMSE) of IRI-2012 vTEC values over GPS-TEC values for all stations across the latitude.

	MARCH EQUINOX			SEPTEMBER EQUINOX			JUNE SOLSTICE			DECEMBER SOLSTICE		
STATIONS	NeQuick	IRI-01 Corr	IRI-2001	NeQuick	IRI-01 Corr	IRI-2001	NeQuick	IRI-01 Corr	IRI-2001	NeQuick	IRI-01 Corr	IRI-2001
RABT	4.31	4.16	4.01	5.27	4.46	5.57	3.89	3.19	4.69	4.42	4.56	5.43
SUTH	3.50	2.16	3.27	4.21	5.20	4.13	2.34	4.96	3.60	8.53	6.67	5.88

4.0 Conclusion

In this study, seasonal variation of vertical TEC is investigated at two mid-latitude stations along the East African sector. The performance of the model, IRI-2012 in modelling the GPS-TEC at these stations is also verified for a year (2010) of low solar activity.

The diurnal seasonal variation shows a sharp increase of electron content during sunrise and later slows down around 10:00 LT. The electron content reaches its maximum just after noon and starts to decrease thereafter as the solar incident rays become more oblique. The minimum values were attained just before sunrise, around 05:00 – 06:00 LT.

The seasons also exhibited daytime depression before noon and after noon for northern and southern hemispheres respectively.

The model estimate showed a good replica of the morphology of TEC, this is evidence in the correlation coefficients. The model options (NeQuick, IRI-2001 and IRI01 Corr) generally underestimated GPS-derived TEC during the pre-sunrise, overestimated it at daytime and later underestimated TEC later in the day. The model options performed well at different seasons for the two stations. The overall best option could not be ascertained at this region as compared to other works done for the other regions; equatorial and low latitude regions during low solar activity.

References

[1] A. D. Richmond, "Ionospheric Electrodynamics Using Magnetic Apex Coordinates.," *J. Geomagn. Geoelectr.*, vol. 47, no. 2, pp. 191–212, 1995.

[2] T. J. Fuller-Rowell, M. V. Codrescu, R. G. Roble, and A. D. Richmond, "How does the thermosphere and ionosphere react to a geomagnetic storm?," 1997, pp. 203–225.

[3] A. DasGupta, A. Paul, and A. Das, "Ionospheric total electron content (TEC) studies with GPS in the equatorial region," *Indian J. Radio Sp. Phys.*, vol. 36, no. 4, pp. 278–292, 2007.

[4] S. Mukherjee, S. Sarkar, P. K. Purohit, and A. K. Gwal, "Seasonal variation of total electron content at crest of equatorial anomaly station during low solar activity conditions," *Adv. Sp. Res.*, vol. 46, no. 3, pp. 291–295, 2010.

[5] S. Kumar and A. K. Singh, "Storm time response of GPS-derived total electron content (TEC) during low solar active period at Indian low latitude station Varanasi," *Astrophys. Space Sci.*, vol. 331, no. 2, pp. 447–458, Feb. 2010.

[6] S. Kumar, S. Priyadarshi, G. G. Krishna, and A. K. Singh, "GPS-TEC variations during low solar activity period (2007-2009) at Indian low latitude stations," *Astrophys. Space Sci.*, vol. 339, no. 1, pp. 165–178, 2012.

[7] P. V. S. R. Rao, S. G. Krishna, K. Niranjan, and D. S. V. V. D. Prasad, "Annales Geophysicae Temporal and spatial variations in TEC using simultaneous measurements from the Indian GPS network of receivers during the low solar activity period of 2004 – 2005," pp. 3279–3292, 2006.

[8] M. S. Bagiya, H. P. Joshi, K. N. Iyer, M. Aggarwal, S. Ravindran, and B. M. Pathan, "TEC variations during low solar activity period (2005-2007) near the equatorial ionospheric anomaly crest region in India," *Ann. Geophys.*, vol. 27, no. 3, pp. 1047–1057, 2009.

[9] S. Kumar and A. K. Singh, "Variation of ionospheric total electron content in Indian low latitude region of the equatorial anomaly during May 2007-April 2008," *Adv. Sp. Res.*, vol. 43, no. 10, pp. 1555–1562, 2009.

[10] S. Kumar and A. K. Singh, "Storm time response of GPS-derived total electron content (TEC) during low solar active period at Indian low latitude station Varanasi," *Astrophys. Space Sci.*, vol. 331, no. 2, pp. 447–458, 2010.

[11] P. Galav, S. Sharma, and R. Pandey, "Study of simultaneous penetration of electric fields and variation of total electron content in the day and night sectors during the geomagnetic storm of 23 May 2002," *J. Geophys. Res. Sp. Phys.*, vol. 116, no. 12, pp. 1–10, 2011.

[12] J. Oluwadare, E, "Latitudinal variation of total electron content in the east African sector and validation of international reference ionosphere model," University of Ilorin, Nigeria, 2017.

[13] Y.-N. Huang, K. Cheng, and S.-W. Chen, "On the Equatorial Anomaly of the Ionospheric Total Electron Content Near the Northern Anomaly Crest Region," *J. Geophys. Res.*, vol. 94525, no. 1, pp. 515–13, 1989.

[14] J. Klobuchar, "Design and characteristics of the GPS ionospheric time-delay algorithm for single-frequency users," in *IEEE Position Location and Navigation Symposium*, 1986.

[15] L. Scherliess, R. W. Schunk, J. J. Sojka, D. C. Thompson, and L. Zhu, "Utah State University Global Assimilation of Ionospheric Measurements Gauss-Markov Kalman filter model of the ionosphere: Model description and validation," *J. Geophys. Res. Sp. Phys.*, vol. 111, no. 11, pp. 1–12, 2006.

[16] B. Nava, P. Coïsson, and S. M. Radicella, "A new version of the NeQuick ionosphere electron density model," *J. Atmos. Solar-Terrestrial Phys.*, vol. 70, no. 15, pp. 1856–1862, Dec. 2008.

[17] D. N. Anderson, M. Mendillo, and B. Herniter, "A semi-empirical low-latitude ionospheric model," *Radio Sci.*, vol. 22, no. 2, pp. 292–306, Mar. 1987.

[18] D. Bilitza, "International Reference Ionosphere 2000 of ionospheric It was and the F peak down to," *Radio Sci.*, vol. 36, no. 2, pp. 261–275, 2001.

[19] D. Bilitza and B. W. Reinisch, "International Reference Ionosphere 2007: Improvements and new parameters," *Adv. Sp. Res.*, vol. 42, no. 4, pp. 599–609, Aug. 2008.

[20] R. G. Ezquer, N. Ortiz de Adler, S. M. Radicella, M. Mosert de Gonzalez, and J. R. Manzano, "IRI and BPM total electron content predictions for Tucuman," *Adv. Sp. Res.*, vol. 15, no. 2, pp. 121–124, 1995.

[21] B. D. L. Opperman, P. J. Cilliers, L. A. McKinnell, and R. Haggard, "Development of a regional GPS-based ionospheric TEC model for South Africa," *Adv. Sp. Res.*, vol. 39, no. 5, pp. 808–815, 2007.

[22] A. O. Olawepo, J. O. Adeniyi, and E. J. Oluwadare, “TEC variations and IRI-2012 performance at equatorial latitudes over Africa during low solar activity,” *Adv. Sp. Res.*, vol. 59, no. 7, pp. 1800–1809, Apr. 2017.
[23] D. Bilitza, D. Altadill, Y. Zhang, C. Mertens, V. Truhlik, P. Richards, L. Mckinnell, and B. Reinisch, “The International Reference Ionosphere 2012 – a model of international collaboration I,” vol. 4, 2014.
[24] M. M. de G. Ezquer, R.G, Jadur, C, A, “IRI-95 TEC predictions for the South Amer- ican peak of the equatorial anomaly,” *Adv. Sp. Res.*, vol. 22, no. 6, pp. 811–814, 1998.
[25] M. R. Rama Rao, P.V.S., Nru, D. and Srirama, “Study of some low latitude ionospheric phenomenon observesd in TEC measurements at Waltair, India.,” in *Scientific and Engineering uses of Satellite Radio Beacons, COSPAR/URSI Symposium*, 1980, pp. 175–187.
[26] V. Chauhan and O. P. Singh, “A morphological study of GPS-TEC data at Agra and their comparison with the IRI model,” *Adv. Sp. Res.*, vol. 46, no. 3, pp. 280–290, 2010.
[27] A. B. Rabiu, A. O. Adewale, R. B. Abdulrahim, and E. O. Oyeyemi, “TEC derived from some GPS stations in Nigeria and comparison with the IRI and NeQuick models,” *Adv. Sp. Res.*, vol. 53, no. 9, pp. 1290–1303, 2014.
[28] D. Okoh, L. Mckinnell, P. Cilliers, and B. Okere, “IRI-vTEC versus GPS-vTEC for Nigerian SCINDA GPS stations,” *Adv. Sp. Res.*, vol. 55, no. 8, pp. 1941–1947, 2015.
[29] F. Ouattara, C. Zoundi, and R. Fleury, “Comparison between CODG TEC and GPS based TEC observations at Koudougou station in Burkina Faso,” *Indian J. Radio Sp. Phys.*, vol. 41, pp. 617–623, 2012.
[30] A. O. Akala, G. K. Seemala, P. H. Doherty, C. E. Valladares, C. S. Carrano, J. Espinoza, and S. Oluyo, “Comparison of equatorial GPS-TEC observations over an African station and an American station during the minimum and ascending phases of solar cycle 24,” no. 2004, pp. 2085–2096, 2013.
[31] S. Kumar, E. L. Tan, and D. S. Murti, “Impacts of solar activity on performance of the IRI-2012 model predictions from low to mid latitudes,” *Earth, Planets Sp.*, vol. 67, pp. 42, 2015.
[32] A. O. Adewale, E. O. Oyeyemi, J. O. Adeniyi, A. B. Adeloye, and O. A. Oladipo, “Comparison of total electron content predicted using the IRI-2007 model with GPS observations over Lagos , Nigeria,” *Indian J. Radio Sp. Phys.*, vol. 40, pp. 21–25, 2011.
[33] A. O. Adewale, E. O. Oyeyemi, P. J. Cilliers, L. A. McKinnell, and A. B. Adeloye, “Low solar activity variability and IRI 2007 predictability of equatorial Africa GPS TEC,” *Adv. Sp. Res.*, vol. 49, no. 2, pp. 316–326, 2012.
[34] O. J. Olwendo, P. Baki, P. J. Cilliers, C. Mito, and P. Doherty, “Comparison of GPS TEC measurements with IRI-2007 TEC prediction over the Kenyan region during the descending phase of solar cycle 23,” *Adv. Sp. Res.*, vol. 49, no. 5, pp. 914–921, 2012.
[35] O. J. Olwendo, P. Baki, P. J. Cilliers, C. Mito, and P. Doherty, “Comparison of GPS TEC variations with IRI-2007 TEC prediction at equatorial latitudes during a low solar activity (2009-2011) phase over the Kenyan region,” *Adv. Sp. Res.*, vol. 52, no. 10, pp. 1770–1779, 2013.
[36] Y. A. Tariku, “TEC prediction performance of the IRI-2012 model over Ethiopia during the rising phase of solar cycle 24 (2009-2011),” *Earth, Planets Sp.*, vol. 67, no. 1, pp. 1–10, 2015.
[37] Krishna S. G, “GPS-TEC analysis application.” Institute for Scientific Research, Boston College, 140 Commonwealth Avenue, Chestnut Hill, MA - 02467, U.S.A, pp. 1–7, 2009.
[38] O. S. Bolaji, J. O. Adeniyi, S. M. Radicella, and P. H. Doherty, “Variability of total electron content over an equatorial West African station during low solar activity,” vol. 47, no. January, pp. 1–9, 2012.
[39] J. O. Adeniyi, P. H. Doherty, O. A. Oladipo, and O. Bolaji, “Magnetic storm effects on the variation of TEC over Ilorin an equatorial station,” *Radio Sci.*, vol. 49, no. 12, pp. 1245–1253, 2014.
[40] P. Opio, F. M. D’Ujanga, and T. Ssenyonga, “Latitudinal variation of the ionosphere in the African sector using GPS TEC data,” *Adv. Sp. Res.*, vol. 55, no. 6, pp. 1640–1650, 2015.
[41] E. . Oluwadare, J. . Adeniyi, I. . Ademula, O. . Oladipo, and A. . Olawepo, “Latitudinal Dependence of Vertical Total Electron Content in the Equatorial and Low Latitude Regions of the African Sector,” in *URSI-NG Conference*, 2015, pp. 21–28.
[42] P. K. Purohit, P. Bhawre, A. A. Mansoori, P. A. Khan, and A. K. Gwal, “GPS Derived Total Electron Content (TEC) Variations over Indian Antarctica Station , Maitri,” pp. 597–599, 2011.
[43] K. Sharma and R. S. D. Sudha, “Study of total electron content variations over equatorial and low latitude ionosphere during extreme solar minimum,” pp. 277–286, 2012.
[44] J. O. Adeniyi, O. A. Oladipo, and S. M. Radicella, “Variability of foF2 for an equatorial station and comparison with the foF2 maps in IRI model,” vol. 69, pp. 721–733, 2007.
[45] J. O. Adeniyi, S. M. Radicella, I. A. Adimula, and A. A. Willoughby, “Validation of B 0 and B 1 in the IRI 2001 model at low solar activity for Ilorin an equatorial station,” vol. 42, pp. 691–694, 2008.

[46] O. F. Jonah, "ANALYSIS OF TOTAL ELECTRON CONTENT (TEC) VARIATIONS OBTAINED FROM GPS DATA OVER SOUTH AMERICA Dissertation Master at Graduation Course in Space Geophysics , ad- vised by Drs . Eurico Rodrigues de Severino Luiz Guimar ˜ aes Dutra , approved in," 2013.

[47] S. M. Radicella and J. O. Adeniyi, "Equatorial ionospheric electron density below the F 2 peak," *Radio Sci.*, vol. 34, no. 5, pp. 1153–1163, 1999.

[48] C. C. Lee, B. W. Reinisch, S. Su, and W. S. Chen, "Quiet-time variations of F2-layer parameters at Jicamarca and comparison with IRI-2001 during solar minimum," vol. 70, pp. 184–192, 2008.

[49] N. J. Skinner, "Measurements of total electron content near the magnetic equator," *Planet. Space Sci.*, vol. 14, no. 11, pp. 1123–1129, 1966.

[50] G. Rajaram and R. G. Rastogi, "Equatorial electron densities-seasonal and solar cycle changes," *J. Atmos. Terr. Phys.*, vol. 39, no. 9–10, pp. 1175–1182, 1977.

[51] D. Okoh, A. Eze, O. Adedoja, B. Okere, and P. N. Okeke, "A comparison of IRI-TEC predictions with GPS-TEC measurements over Nsukka, Nigeria," *Sp. Weather*, vol. 10, no. 10, pp. 1–6, 2012.