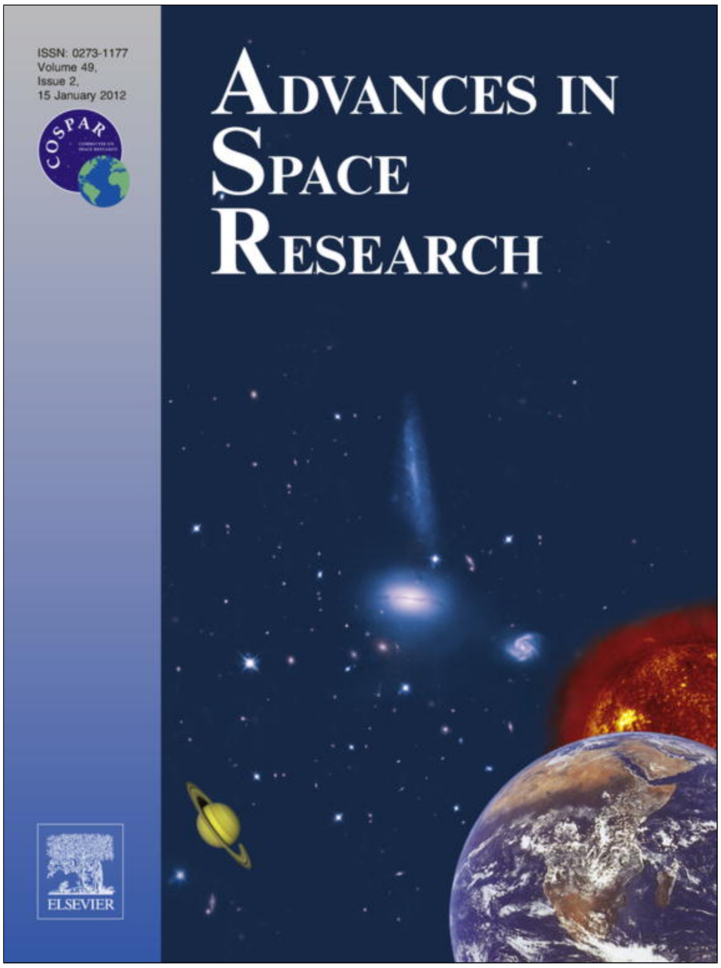
ISSN: 0273-1177
Volume 49,
Issue 2,
15 January 2012
COSPAR
ADVANCES IN SPACE RESEARCH
ELSEVIER

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Advances in Space Research 49 (2012) 316–326

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Low solar activity variability and IRI 2007 predictability of equatorial Africa GPS TEC

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Received 11 July 2011; received in revised form 28 September 2011; accepted 29 September 2011
Available online 7 October 2011

Abstract

Diurnal, seasonal and latitudinal variations of Vertical Total Electron Content (VTEC) over the equatorial region of the African continent and a comparison with IRI-2007 derived TEC (IRI-TEC), using all three options (namely; NeQuick, IRI01-corr and IRI-2001), are presented in this paper. The variability and comparison are presented for 2009, a year of low solar activity, using data from thirteen Global Positioning System (GPS) receivers. VTEC values were grouped into four seasons namely March Equinox (February, March, April), June Solstice (May, June, July), September Equinox (August, September, October), and December Solstice (November, December, January). VTEC generally increases from 06h00 LT and reaches its maximum value at approximately 15h00–17h00 LT during all seasons and at all locations. The NeQuick and IRI01-corr options of the IRI model predict reasonably well the observed diurnal and seasonal variation patterns of VTEC values. However, the IRI-2001 option gave a relatively poor prediction when compared with the other options. The post-midnight and post-sunset deviations between modeled and observed VTEC could arise because NmF2 or the shape of the electron density profile, or both, are not well predicted by the model; hence some improvements are still required in order to obtain improved predictions of TEC over the equatorial region of the Africa sector.

Keywords: Total Electron Content (TEC); IRI; IRI variability; GPS

1. Introduction

Total Electron Content (TEC) is an important descriptive parameter of the ionosphere. TEC represents the total number of electrons present along any path between the Global Positioning System (GPS) satellite and the ground based receiver, with units of electrons per square meter, where 10^{16} electrons/m$^2 = 1$ TEC unit (TECU). Vertical Total Electron Content (VTEC) is a very good indicator of the degree of ionization of the Earth ionosphere and has many practical applications in satellite navigation, time delay and range error corrections for single frequency GPS satellite signal receivers (Bhuyan and Borah, 2007). The position, velocity and time estimates obtained by a GPS receiver depends on TEC, satellite–receiver distance, signal multipath, tropospheric delay, satellite and receiver block offsets, receiver clock errors, orbital errors, satellite geometry, number of satellites visible, phase ambiguities as well as satellite and receiver instrumental biases. Dual frequency GPS measurements can provide integral information about the ionosphere and plasmasphere by computing the differential phases of the code and carrier phase measurements recorded at the ground-based GPS receivers (Yizengaw et al., 2007; Davis and Hartmann, 1997), which is used in evaluating TEC.

Although TEC measurements have been carried out at various sectors around the globe, not much work has been undertaken around the equatorial region of the African

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doi:10.1016/j.asr.2011.09.032

Table 1
Coordinates of GPS receiver locations (arranged in order of increasing geographic latitude).

Stations	Station Code	Geographic		Geomagnetic	
		Latitude°N	Longitude°E	Latitude°N	Longitude°E
Tukuyu, Tanzania	TUKC	−9.33	32.75	−19.61	103.89
Tanzania GGPS, Tanzania	TANZ	−6.77	39.21	−16.59	110.65
Malinda, Kenya	MAL2	−2.99	40.19	−12.42	111.86
Kigali, Rwanda	NURK	−1.94	30.09	−11.62	101.66
Mbarara, Uganda	MBAR	−0.60	30.74	−10.22	102.36
Entebbe, Uganda	EBBE	0.04	32.4	−9.53	104.06
Mt. Baker, Uganda	BAKC	0.35	29.9	−9.25	101.51
Libreville, Gabon	NKLG	0.35	9.67	−8.05	81.05
Lagos, Nigeria	LAGO	6.52	3.39	−3.03	75.44
Yamoussoukro, CoteD'Ivoire	YKRO	6.87	354.76	−2.56	67.41
Robe, Ethiopia	ROBE	7.11	40.02	−1.69	111.77
Ilorin, Nigeria	ILOR	8.48	4.67	−1.84	76.79
Nazret, Ethiopia	NAZR	8.57	39.29	−0.25	111.01

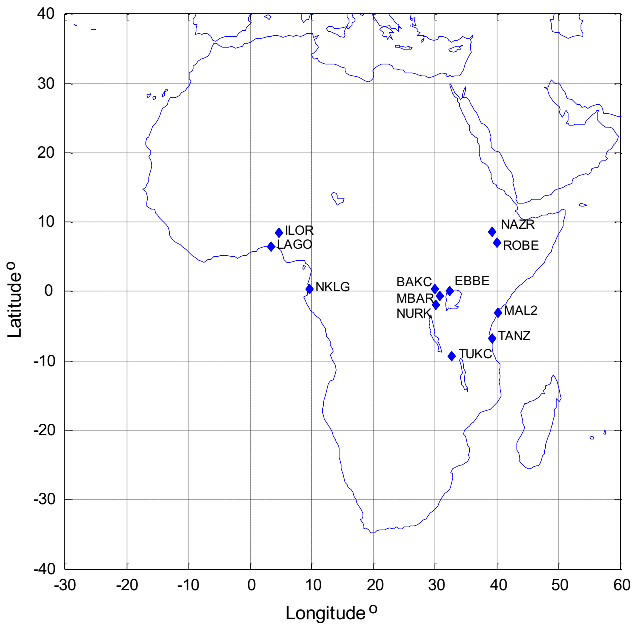

Fig. 1. Map of Africa showing the locations of the GPS receiver stations used in this study.

continent and this has affected the availability of data for continuous ionospheric studies. Several models (e.g. IRI (Bilitza, 2001; Bilitza and Reinisch, 2008), SLIM (Anderson et al., 1987), GCPM-2000 (Gallagher et al., 2000), and NeQuick (Nava et al., 2008)) have been developed to solve the problem of non-availability of continuous data for all latitudes around the globe. The International Reference Ionosphere (IRI) is the most commonly used model. The IRI project is a joint programmed of the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI) initiated in the late 60s with the aim of launching an international standard for the specification of ionospheric parameters based on available data from ground-based as well as satellite observations. IRI is an empirical ionospheric model based on experimental observations of the ionospheric plasma. The IRI model describes monthly averages of the electron density, electron temperature, ion composition, ion temperature, and ion drift in the current altitude range of 50–2000 km. The IRI model provides three options for the prediction of TEC, namely: IRI-2001 (Bilitza, 2001), IRI01-Corr (Bilitza, 2004) and NeQuick (Radicella and Leitinger, 2001; Coïsson et al., 2006).

The accuracy of the IRI model in a specific region and/or time period depends on the availability of reliable data for the specific region and time since it is a data-based model. The IRI is continually improved as new data and new modeling techniques become available and this process has resulted in several versions of IRI (Rawer et al., 1978a,b, 1981; Bilitza, 1990, 2001; Bilitza and Reinisch, 2008). Bilitza and Reinisch (2008) reported that IRI predictions are most accurate over the Northern mid-latitudes because of the generally high ionosonde density in this part of the globe. Several authors (e.g. McNamara, 1985; Sethi et al., 2001) have reported the inability of older versions of the IRI model to predict TEC values at various ionospheric stations. This limitation of IRI has been improved in the latest version (IRI-2007) by applying "NeQuick" (Coïsson et al., 2008a). Coïsson et al. (2008b) reported that within IRI2007 the NeQuick option improved the estimate of TEC over predictions made with IRI2001. A number of papers have published on comparative studies of TEC with the IRI model over the equatorial region (Adewale et al., 2011; Sethi et al., 2011; Obrou et al., 2009; Bhuyan and Borah, 2007; Yuan et al., 1995). Out of these comparative studies, only Adewale et al. (2011) and Obrou et al. (2009) used data from the equatorial African sector and they have only used data from a single station. Obrou et al. (2009) while comparing TEC derived from ionosonde data recorded at the station of Korhogo (9.33°N, 5.43°W, dip latitude = 0.67°S) with predictions from IRI-2001, reported that the relative deviation, ΔTEC, is prominent in the equinoctial seasons during nighttime hours where it is as high as 70%. During daytime hours, the relative deviation is estimated to be below 30%. Recently, Adewale et al. (2011), using data from Lagos (6.5°N, 3.4°E; dip latitude 2°S), reported that IRI-2007 (NeQuick option) gave a relatively poor TEC prediction between 02h00 and 06h00 LT, with the TEC percentage deviation (ΔTEC) having values greater than 50% during all seasons considered in year 2009. The ΔTEC never exceeded 50% at any other hour of the day except at 08h00 LT during both December Solstice and September Equinox.

The purpose of this research is to study the diurnal, seasonal, and latitudinal variations of GPS-TEC over the equatorial region of Africa, using data from thirteen GPS stations and to validate the IRI-2007 version, using all three options.

2. Data and method of analysis

The data used for this research were obtained from the Low-latitude Ionospheric Sensor Network (LISN) (http://www.jro.igp.gob.pe/lisn), Scripps Orbit and Permanent Array Center (SOPAC) (http://www.sopac.ucsd.edu) and UNAVCO websites. LISN is a project led by Boston College in collaboration with the Geophysical Institute of Peru, and other institutions that provide information for the benefit of the scientific community. SOPAC is an International GPS Service (IGS) Global Data Center. UNAVCO is a non-profit membership-governed consortium that facilitates geoscience research and education using geodesy. The coordinates of the thirteen stations used for this study are given in Table 1. Fig. 1 shows a map of Africa indicating the location of the GPS receivers.

The RINEX observation files obtained from these websites were processed by the GPS–TEC analysis application software, developed by Gopi Seemala of the Institute for Scientific Research, Boston College, U.S.A.

The software calculates VTEC from the observation data using a suitable mapping function. The mapping function $S(E)$ is given by

$$S(E) = \frac{1}{cos(z)} = \left\{1 - \left(\frac{R_E \times cos(E)}{R_E + h_s}\right)^2\right\}^{-0.5} \tag{1}$$

with

z = zenith angle of the satellite as seen from the observing station,
R_E = radius of the Earth,
E = the elevation angle in radians, and
h_s = the altitude of the thin layer above the surface of the Earth (taken as 350 km)

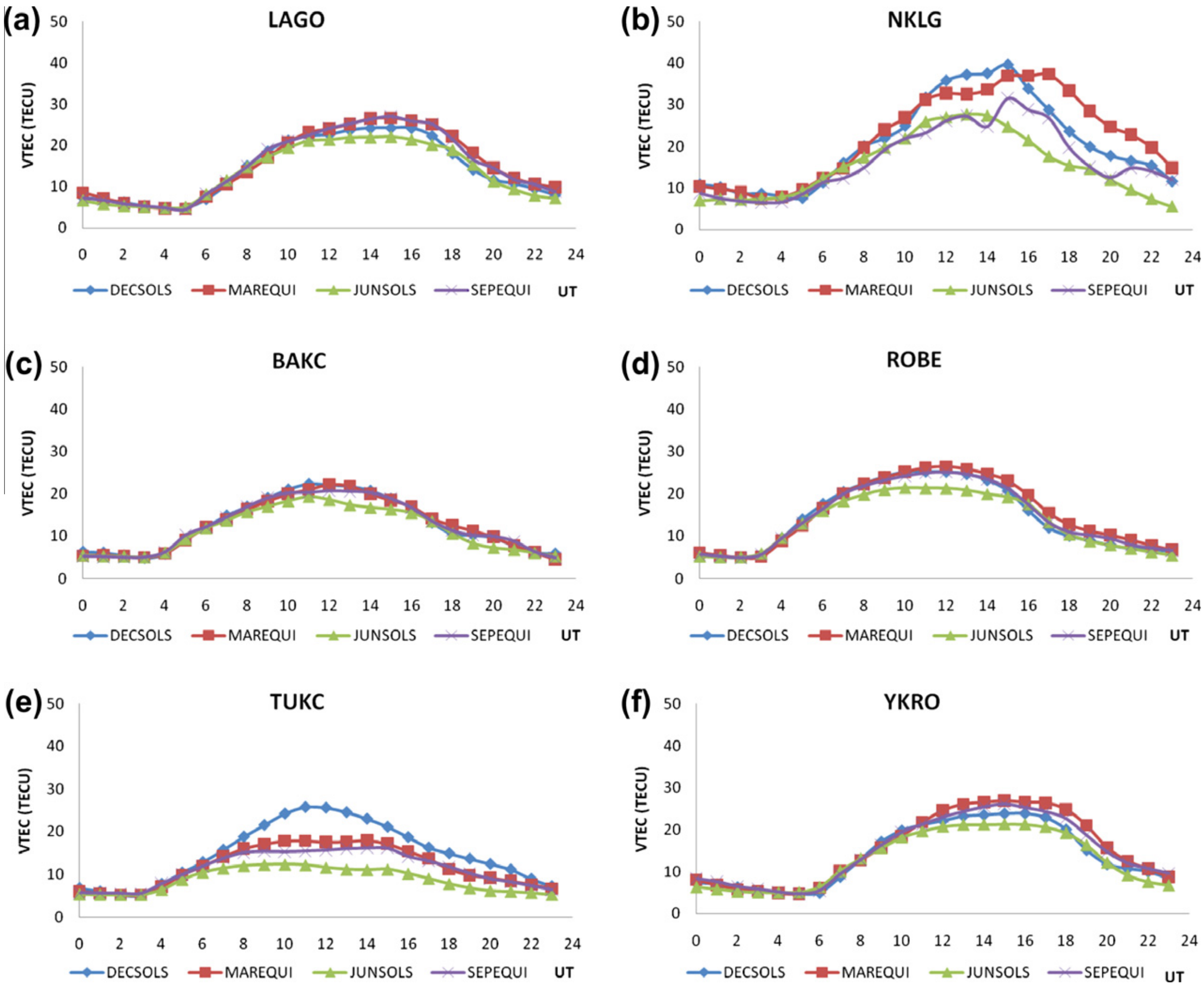

Fig. 2. Diurnal and seasonal variations of VTEC for six selected stations.

In order to minimize the multipath effects on GPS data, an elevation angle cut off of 20° was used. In addition to eliminating the errors from multipath, we also removed the satellite and receiver biases from the TEC values used in this present study. The satellite and receiver bias values were obtained from the data centre of Bern University, Switzerland. We have used hourly mean values of VTEC for March Equinox (MAREQUI) (February, March, April), June Solstice (JUNSOLS) (May, June, July), September Equinox (SEPEQUI) (August, September, October), and December Solstice (DECSOLS) (November, December, January), for the year 2009 only, due to unavailability of simultaneous data for other years in all the stations.

In other to determine the variability of the experimental data, the methodology involves the use of error bars and the coefficient of variability. The error bars, using standard deviation, were included in the observed VTEC plots. The coefficient of VTEC variability was evaluated using the monthly mean (μ) of the VTEC values and their corresponding standard deviations (σ). The coefficient of variability (CV) is statistically defined as:

$$CV(\%) = \frac{\sigma}{\mu} \times 100 \tag{2}$$

The coefficient of variability is a statistical tool that describes the extent of spread or deviation of each data point from the calculated mean for the entire data set. Bilitza et al. (2004) and Araujo-Pradere et al. (2004) reported that the standard deviation approach provides a good method of describing average deviation from the mean.

The observed values of VTEC are compared with the values modeled by the IRI-2007. TEC values from IRI-2007 model were obtained from the IRI web interface (http://www.ccmc.gsfc.nasa.gov/modelweb/models/iri_vitmo.php). We selected 2000 km as the upper boundary of electron density profiles and the B0 Table option for the bottomside electron density shape parameter.

The percentage deviation between the IRI-2007 model results and the (GPS) observed values of the VTEC were also analysed, according to the following equation:

$$\mathrm{PD\_VTEC_i} = \frac{\mathrm{VTEC\_IRI_i} - \mathrm{VTEC\_OBS_i}}{\mathrm{VTEC\_OBS_i}} \times 100 \tag{3}$$

where $\mathrm{VTEC\_OBS_i}$ and $\mathrm{VTEC\_IRI_i}$ represent the (GPS) observed and (IRI) modeled VTEC values respectively.

Also, the root-mean-square error (RMSE) has been used here to evaluate the performance of the IRI-2007;

$$\mathrm{RMSE} = \sqrt{\sum_{i=1}^{N} \frac{1}{N} (\mathrm{VTEC_{obs}} - \mathrm{VTEC_{IRI}})^2} \tag{4}$$

$$\mathrm{RMSE_{average}} = \frac{1}{k} \sum_{j=1}^{k} (\mathrm{RMSE})_j$$

where N is the number of data points and $\mathrm{VTEC_{obs}}$ and $\mathrm{VTEC_{IRI}}$ are the observed and modeled VTEC values, respectively.

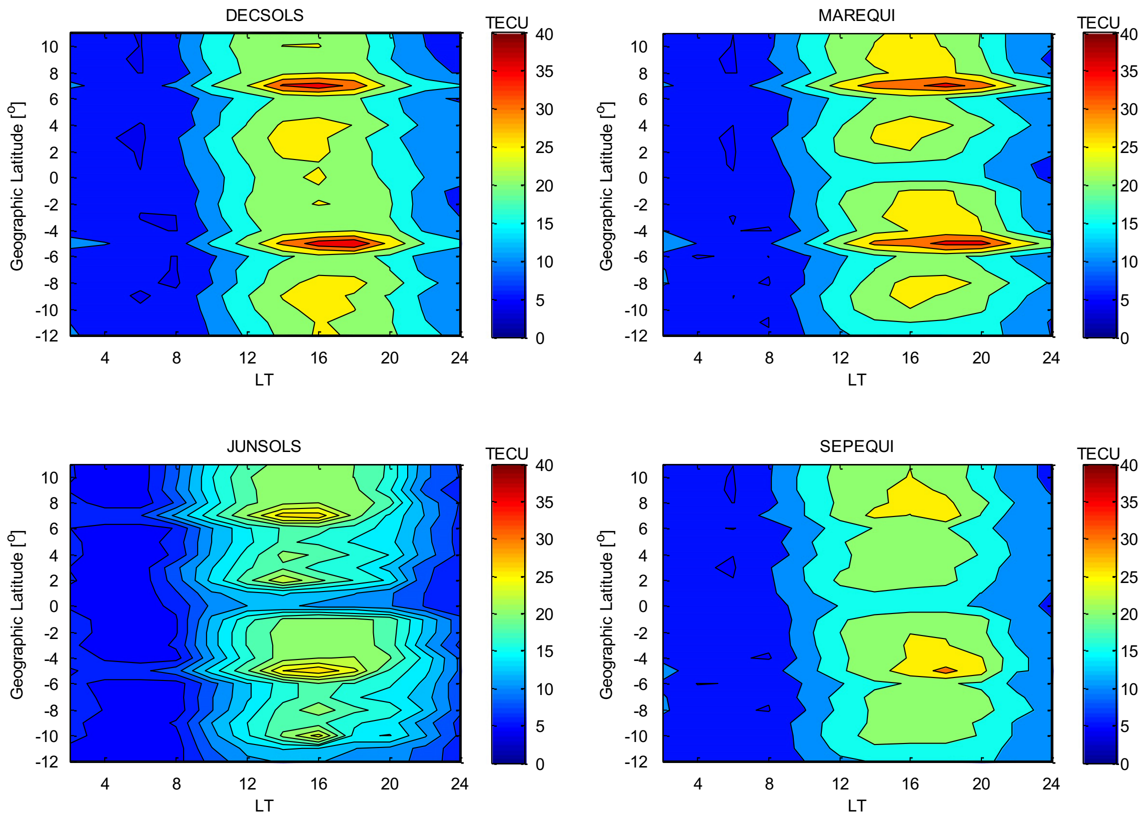

Fig. 3. Contour plot of monthly mean VTEC for DECSOLS, MAREQUI, JUNSOLS and SEPEQUI.

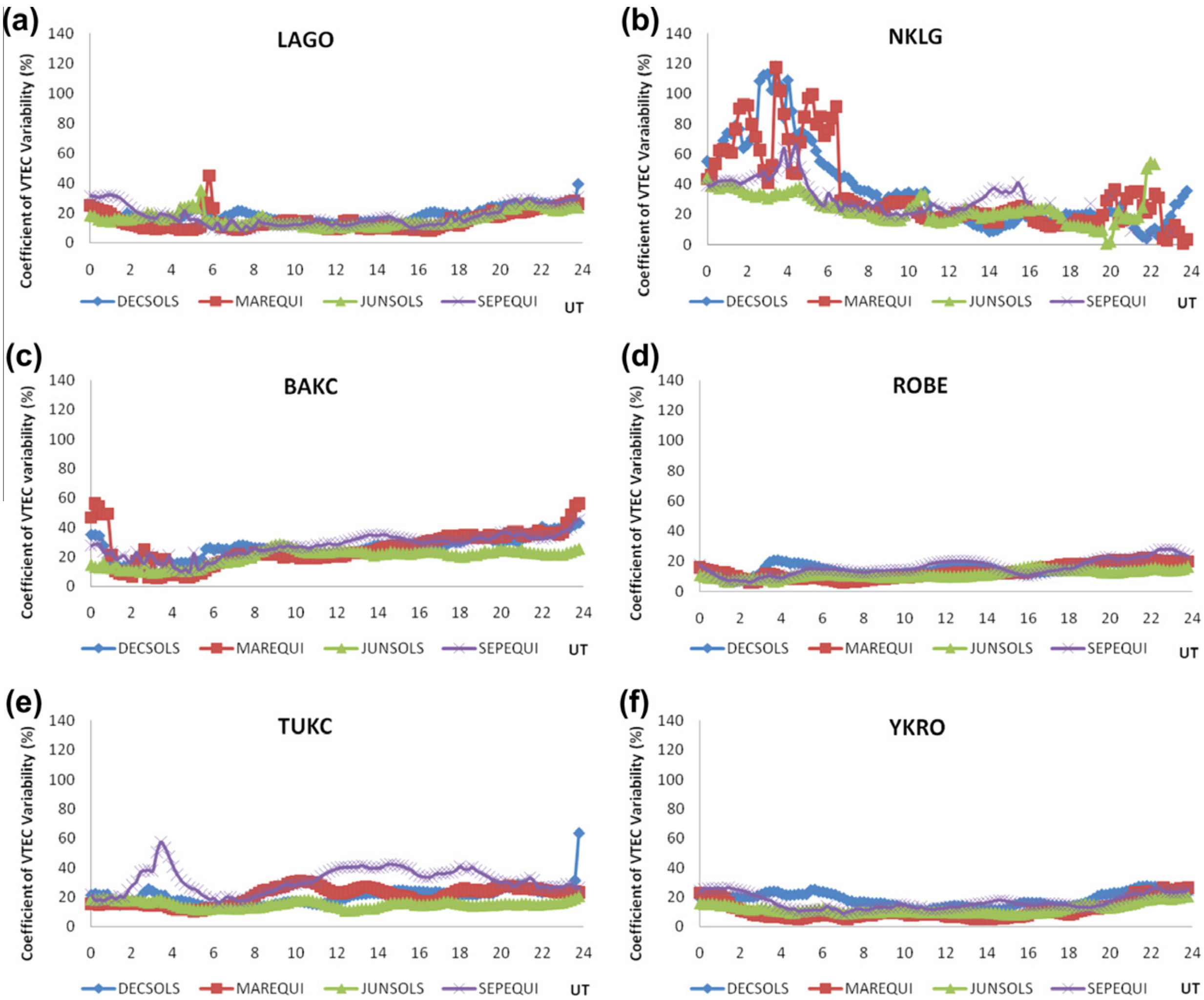

Fig. 4. Coefficient of VTEC variability (*CV*) for six selected stations.

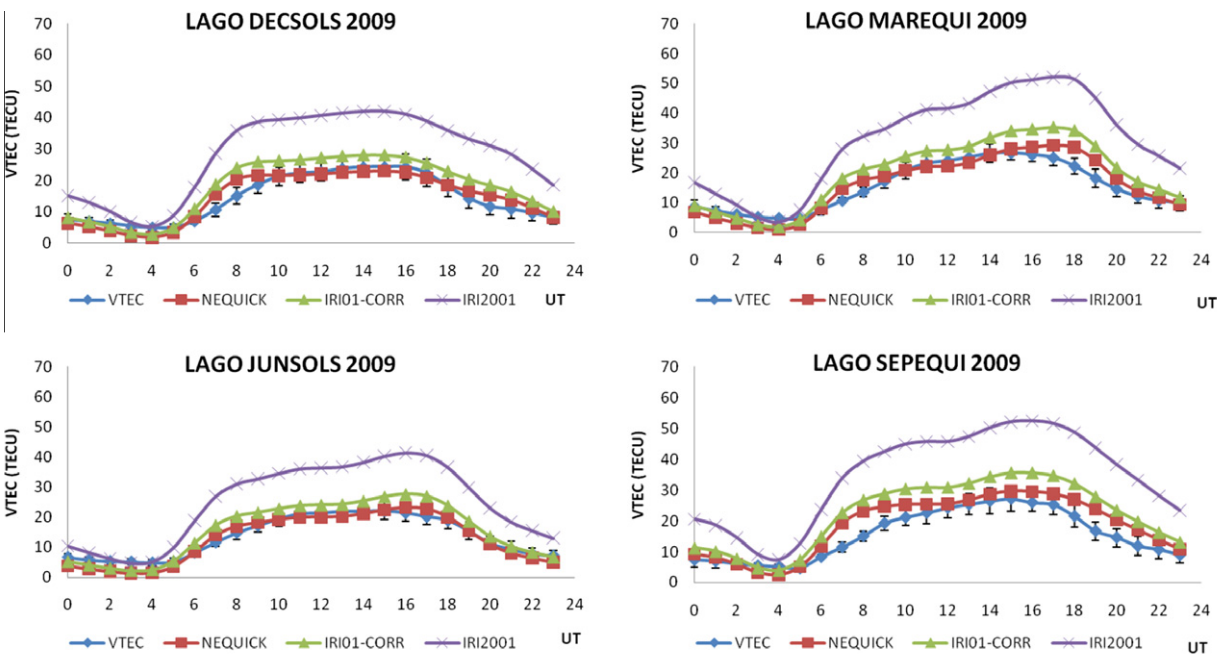

Fig. 5. Diurnal variations of observed mean values of TEC at Lagos along with the IRI-2007 modeled values using the three options.

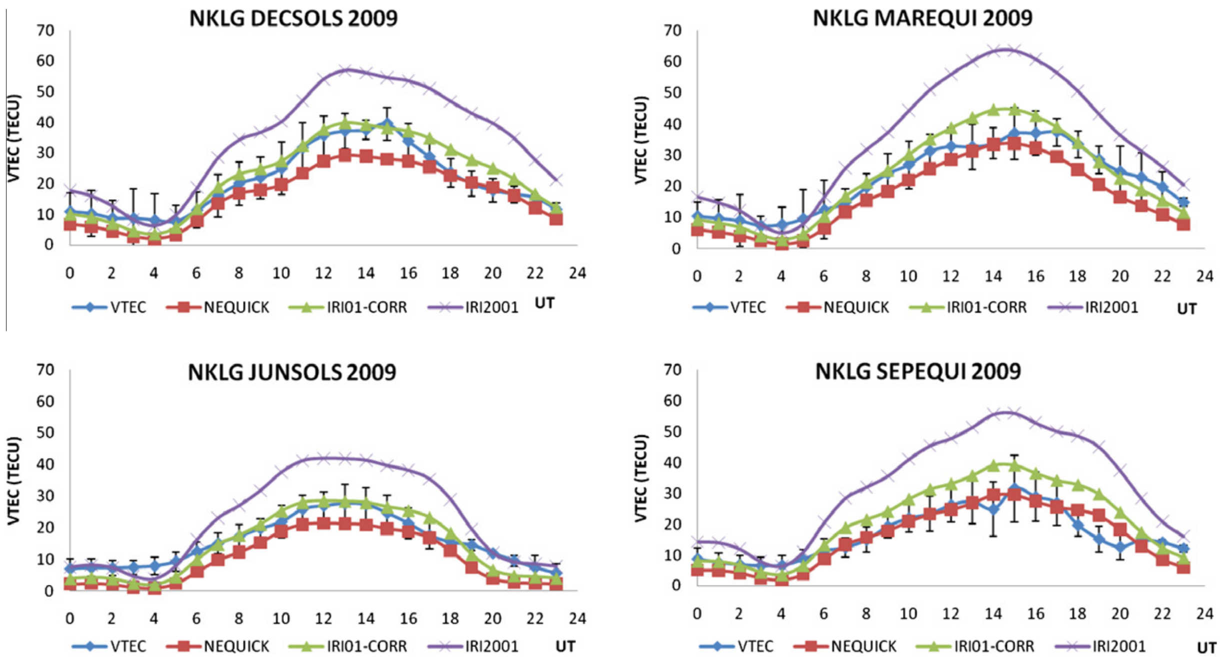

Fig. 6. Diurnal variations of observed mean values of TEC at Libreville along with the IRI-2007 modeled values using the three options.

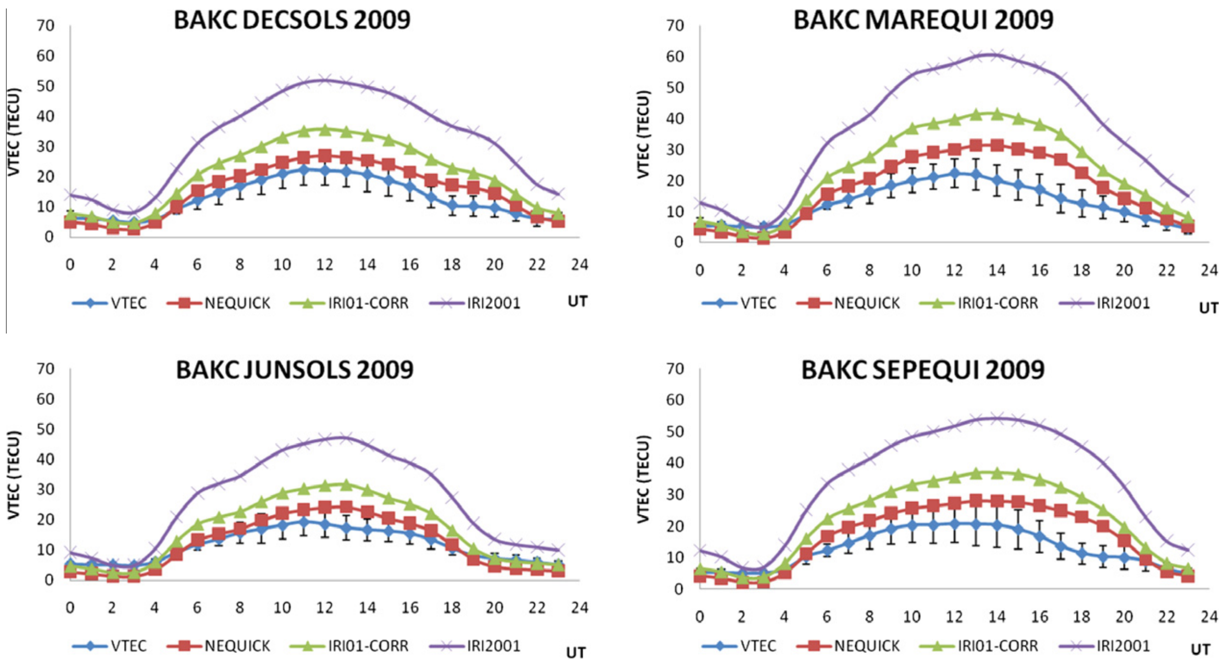

Fig. 7. Diurnal variations of observed mean values of TEC at Mt. Baker along with the IRI-2007 modeled values using the three options.

3. Results and discussion

3.1. Diurnal, seasonal and latitudinal variations

Fig. 2(a)–(f) show the diurnal variation of the monthly mean VTEC for different seasons over six selected stations; LAGO, NKLG, BACK, ROBE, TUKC, and YKRO. GPS–TEC measurements present a very similar behavior for all four seasons, with relatively higher amplitude of diurnal maximum in MAREQUI while JUNSOLS presents the lowest values for all the stations, except at TUKC which is in the southern geographic hemisphere and on the southern crest of the equatorial anomaly. This is because the sun shines directly over the equatorial region during equinoctial months and thus leads to the strongest ionization over these regions. Hence the maximum value of VTEC is observed during the equinoctial season over all the stations. For all the seasons considered, VTEC has higher values during daytime compared with nighttime values over all the stations. At LAGO, VTEC values generally increase from 06h00 LT for all the seasons and reach a maximum value during 15h00–17h00 LT. The amplitude of the diurnal peak is higher

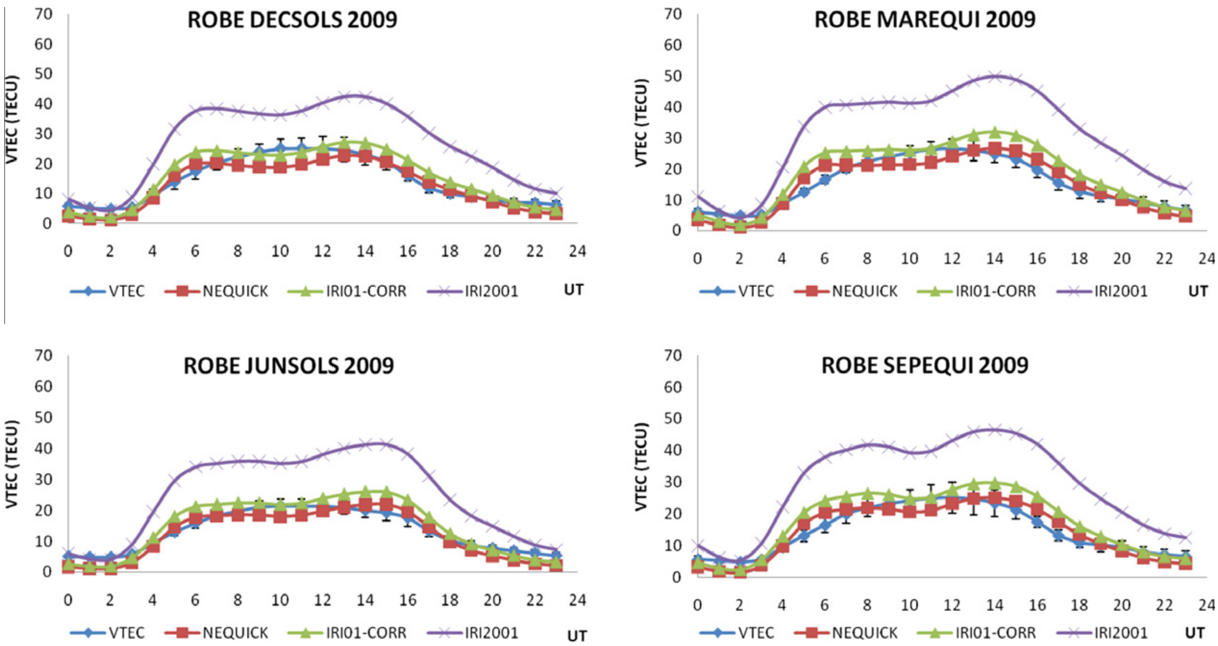

Fig. 8. Diurnal variations of observed mean values of TEC at Robe along with the IRI-2007 modeled values using the three options.

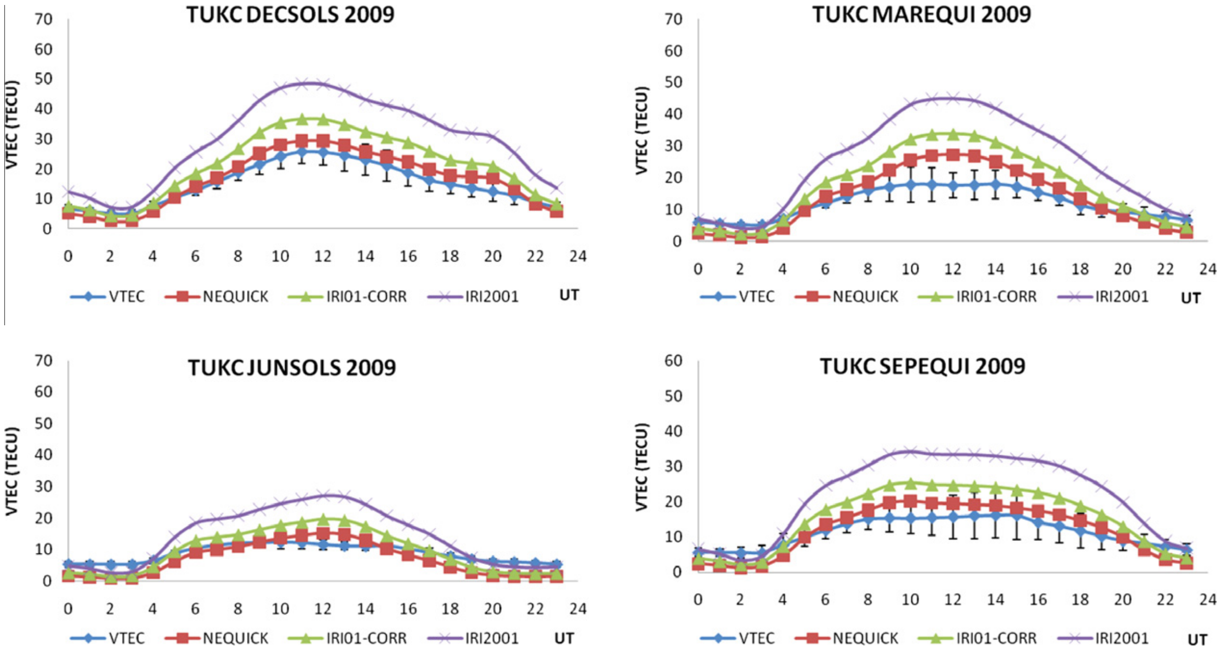

Fig. 9. Diurnal variations of observed mean values of TEC at Tukuyu along with the IRI-2007 modeled values using the three options.

(~27 TECU) for the equinoxes and lower for the solstices thus exhibiting the semiannual variation, which is also noticed at all the other stations. These peaks are found to be associated with smaller chemical losses at higher altitudes, and to the production of solar radiations during daytime (Lee and Reinisch, 2006; Fejer et al., 1991). Rishbeth and Garriott (1969) reported that the production by solar radiation and loss by chemical recombination play important roles in the formation of F2 layer. Observations at LAGO (and at all the other stations) showed the winter anomaly in the seasonal variation. VTEC is higher in the DECSOLS (~24 TECU) compared to the JUNSOLS (~22 TECU). Balan et al. (2000) explained the winter anomaly in terms of winter to summer thermospheric composition ($[O]/[N_2]$) changes. They observed that the equinoctial asymmetry that exists in ($[O]/[N_2]$) and neutral wind velocity could cause corresponding asymmetry in Total Electron Content near the *F*-region peak and above.

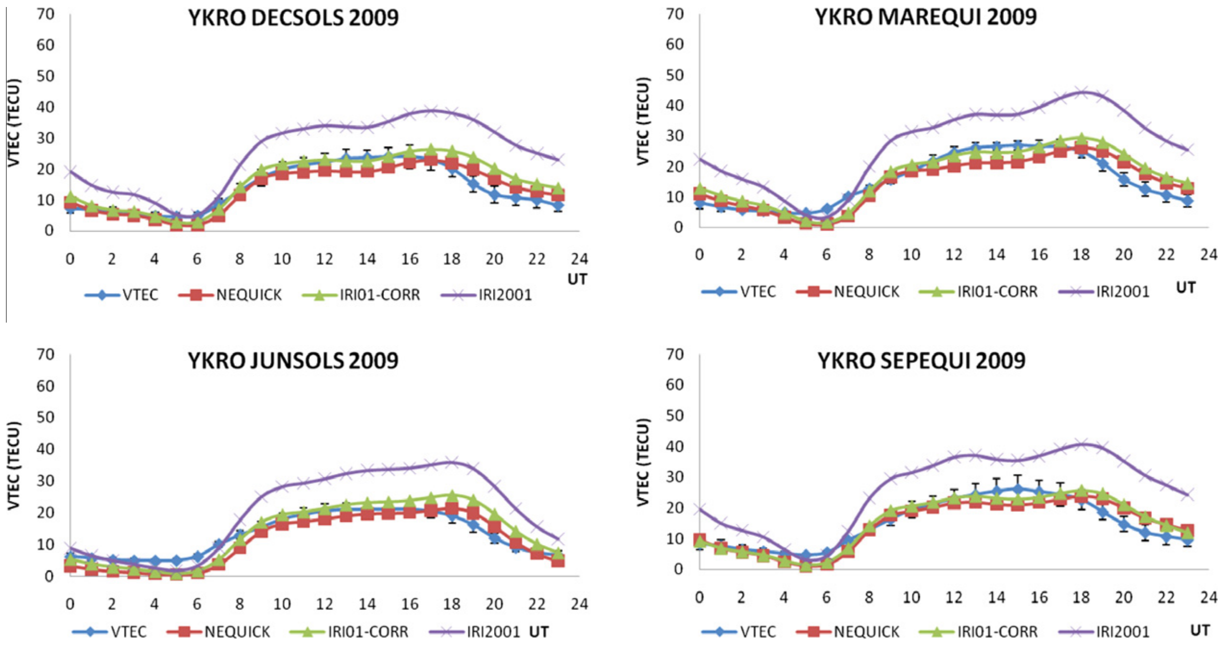

Fig. 10. Diurnal variations of observed mean values of TEC at Yamoussoukro along with the IRI-2007 modeled values using the three options.

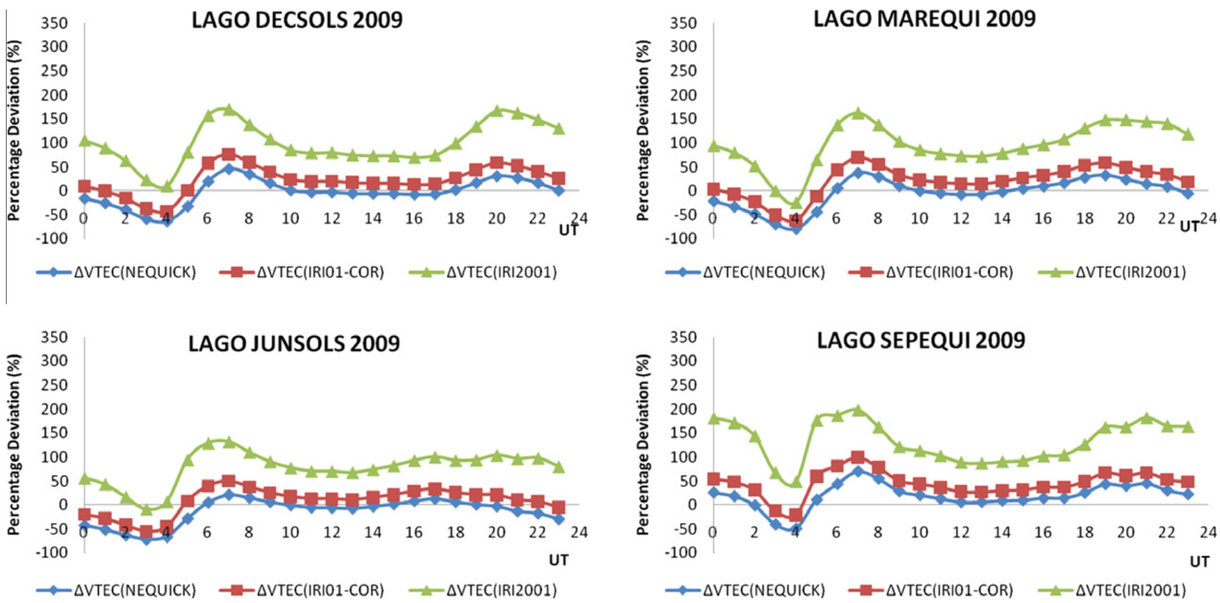

Fig. 11. Percentage deviation plots for Lagos.

Observed VTEC values show a minimum at 06h00 LT and diurnal peak is found between 15h00 and 17h00 LT for all the seasons considered and over all the stations.

Fig. 3 shows the local time versus latitudinal contour plot of VTEC. The figure illustrates the variation of VTEC from latitude −12°–10° for four seasonal periods. In all the seasons, VTEC maximizes around 7°N and 5°S and is higher in both DECSOLS and MAREQUI than in both JUNSOLS and SEPEQUI. The peak around 5°S is at the crest of the equatorial ionization anomaly (EIA). The EIA manifests as a depression in ionization densities (or trough) at the geomagnetic equator and two peaks (or crests) on either side of the equator at about 15° geomagnetic latitudes (Appleton, 1946). According to Mitra (1946), the trough exists because plasma produced by photo-ionization at high altitudes over the magnetic equator diffuses downwards and outwards to the north and south leaving a depletion at the equator.

3.2. Variability of equatorial VTEC

The coefficient of VTEC variability (CV) evaluated from Eq. (2) was plotted against universal time (UT) for six selected stations so as to observe diurnal and seasonal

Table 2
Root mean square error (RMSE) between measured and predicted values of VTEC.

Station	Season	NeQuick	IRI01-corr	IRI2001
BAKC	DECSOLS	3.84	9.52	21.56
	MAREQUI	6.85	13.26	26.65
	JUNSOLS	3.39	7.54	17.65
	SEPEQUI	6.14	11.73	24.32
LAGO	DECSOLS	2.38	4.64	15.19
	MAREQUI	2.95	5.89	17.65
	JUNSOLS	1.96	3.58	12.97
	SEPEQUI	4.13	7.75	20.41
NKLG	DECSOLS	5.40	3.76	15.19
	MAREQUI	5.99	4.55	15.65
	JUNSOLS	5.40	3.33	10.15
	SEPEQUI	3.65	7.17	18.45
ROBE	DECSOLS	2.90	3.15	13.64
	MAREQUI	2.76	4.71	17.33
	JUNSOLS	2.47	3.46	13.73
	SEPEQUI	2.61	4.53	16.44
TUKC	DECSOLS	2.79	7.51	16.19
	MAREQUI	4.86	8.72	16.16
	JUNSOLS	3.20	4.03	8.08
	SEPEQUI	3.17	6.32	12.96
YKRO	DECSOLS	2.76	3.70	12.17
	MAREQUI	3.72	4.00	13.34
	JUNSOLS	3.13	3.71	9.92
	SEPEQUI	3.03	2.86	12.54
	Average RMSE	3.73	5.81	15.76

variabilities at these stations. Fig. 4(a)–(f) show the plot of *CV* based on the monthly mean of VTEC values from the stations. Generally, all the plots have the same diurnal features (comparatively high *CV* during night-time and low during the day). During the day, VTEC variability attains lowest values that range from 5% to 25%, which increases to about 15–60% during night-time, except at NKLG for DECSOLS and MAREQUI with values greater than 100% during the post-midnight hours. All the plots are characterized by two peaks. The highest peak is noted to occur during post-midnight hours and the second peak during post-sunset hours. These two peaks of variability can be attributed to steep electron density gradients that are caused by the onset and turn-off of solar ionization (Bilitza et al., 2004; Chou and Lee, 2008), and superimposition of ionospheric *F* region irregularities (spread *F*) on the background electron density (Woodman and La Hoz, 1976). The values of the *CV* show that TEC exhibits large day-to-day variability irrespective of location. The seasonal and spatial distributions of *CV* are not well-defined. Bhuyan and Borah (2007), while studying the variability of TEC over the Indian subcontinent, also reported that there were no seasonal bias in the variability of TEC.

3.3. Comparison of GPS VTEC with VTEC derived from IRI

Figs. 5–10 show the diurnal plots of the comparison between the observed GPS–VTEC values and IRI-2007 model values using all three options for different seasons over different locations. The diurnal behavior of the GPS–VTEC and IRI-2007 derived VTEC are similar for all the seasons and locations. There is a reasonable agreement between the observed VTEC and the modeled VTEC, except for the IRI-2001 option. Major discrepancies exist between the observations during all seasons and the VTEC modeled by the IRI-2001 option for the six selected locations and at all local times. Our results show that the IRI-2001 option overestimates VTEC for all seasons and locations at all local times. Most importantly, daytime values of IRI-2001 VTEC are very high while NeQuick, IRI01-corr, and GPS–VTEC have almost similar values. The figures show that the minimum VTEC value for IRI-2007 occurred around 05h00–06h00 LT for all the seasons and locations. The time of maximum IRI-2007 TEC value occurred during the 15h00–17h00 LT period. Generally, NeQuick TEC values are the lowest for all seasons while values of IRI01-corr TEC are higher than NeQuick and lower than IRI-2001.

In all the seasons considered and at all locations, NeQuick and IRI01-corr options consistently underestimate the observed VTEC during post-midnight and post-sunset hours, with the VTEC percentage deviation (ΔTEC) having values greater than 50%, as shown in Fig. 11(a)–(d) for LAGO plots. The ΔTEC never exceeded 50% at any other hour of the day for all the seasons and at all locations. These post-midnight and post-sunset deviations between modeled and observed VTEC could arise because either the NmF2 or the shape of the electron density profile, or both, are not well modeled by the NeQuick, IRI01-corr and IRI2001 options. Ezquer et al. (1998) also attributed this discrepancy to the profile shape in the IRI model. NeQuick and IRI01-corr TEC varies mostly between 0% and 50% while IRI-2001 TEC varies up to 300%.

Table 2 shows the root mean square error (RMSE) between measured and modeled values of VTEC of the IRI-2007 model for all the seasons and locations. As can be observed from Table 2 the RMSE values obtained for the three options of the IRI-2007 model justify the fact that NeQuick option performed better than both IRI01-corr and IRI-2001 options, since in almost all cases the NeQuick option RMSE is smaller than that of the IRI01-corr and IRI-2001 options. For the IRI01-corr option the RMSE is only smaller at NKLG during DECSOLS, MAREQUI, and JUNSOLS and at YKRO during SEPEQUI.

Chauhan and Singh (2010) showed that during the daytime GPS–TEC is in close agreement with NeQuick and IRI01-corr while corresponding nighttime values are very close to IRI-2001. In contrast, Sethi et al. (2011) reported that over an equatorial station, the agreement between the IRI01-corr and TEC observations is better during daytime; while outside this time period, NeQuick predictions reveal better agreement. However, our result showed that agreement between observed TEC and NeQuick predictions is better during daytime and nighttime over the equatorial African sector. Chauhan and Singh (2010) used data from a low-mid-latitude station in the Indian sector and Sethi et al. (2011) used data from only one equatorial station from the Indian sector, both during a low solar activity period. Our results are considered more representative of a low solar activity period since we have used data from thirteen equatorial GPS stations.

4. Conclusion

This paper examined VTEC variation over thirteen equatorial stations over the African sector during the year 2009, a year of low solar activity (with an average sunspot number of 3.1) and also considered the validation of the IRI-2007 model VTEC values, using all three available options. VTEC values generally increase from 06h00 LT and reach a maximum value during 15h00–17h00 LT. The results show that the IRI-2007 modeled values follow the diurnal and seasonal variation patterns of the observed values of VTEC. However, there seems to be a large overestimation between observed values and the IRI model when the IRI-2001 option is used. For all seasons and at all locations considered in this work, the three IRI options showed a poor prediction during post-midnight and post-sunset hours when compared with the prediction at other times. In general, NeQuick predictions provide an improvement during daytime and nighttime at the African equatorial stations. Data is currently being archived from these stations to allow for a similar study during high solar activity.

Acknowledgements

The first author acknowledges support from South African National Space Agency (SANSA), Hermanus, South Africa and the University of Lagos, Nigeria. He also acknowledges support from University of Lagos for the Faculty of Science PhD research grant. The GPS data used for this research were obtained from the Low-latitude Ionospheric Sensor Network (LISN) (http://www.jro.igp.gob.pe/lisn), Scripps Orbit and Permanent Array Center (SOPAC) (http://www.sopac.ucsd.edu) and UNAVCO websites. We are also thankful to the Community Coordinated Modeling Center (CCMC) for making the IRI available on website http://www.ccmc.gsfc.nasa.gov/modelweb/models/iri_vitmo.php

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