A comparison of IRI-TEC predictions with GPS-TEC measurements over Nsukka, Nigeria

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[1] The International Reference Ionosphere (IRI) model has been widely adopted as the international standard for specifying ionospheric parameters. An evaluation on the performance of the IRI model (version 2007) over Nsukka, Nigeria (Geographic: 6.87°N, 7.38°E; Geomagnetic: 8.47°N, 81.07°E) is presented in this work. We compare Total Electron Content (TEC) values for year 2010 from the IRI model with corresponding TEC data from the SCINDA (Scintillation Network Decision Aid) GPS receiver installed at Nsukka so as to evaluate the performance of the model over the Nsukka region. Given the proliferation of dual-frequency GPS receivers over the African continent, data from these equipment is proposed for use in TEC modeling over the continent together with the IRI model. Knowledge on the performance of the IRI over various regions of the continent will inform the extent to which the model will be used. The development of more accurate TEC maps find useful applications in enhancing the extent to which ionospheric influences on radio signals (as in single frequency GPS receivers) are corrected. Our results show very good diurnal correlations (above 0.88) between the IRI-TEC predictions and the GPS-TEC measurements for the days examined, and so reveal the potential of the IRI model as a good candidate for an enhanced TEC modeling over the African region.

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1. Introduction

[2] The ionosphere is the region of our atmosphere characterized by the presence of ionized plasma. The region extends in altitudes of about 50 km to 1000 km from the Earth's surface, and is characterized by the presence of an amount of ionized plasma that can have substantial influence on radio propagation through it. Due to the ionosphere's dispersive nature, radio signals propagating through it experience frequency-dependent group delays and phase advances [*Opperman et al.*, 2007]. Increased knowledge of the ionosphere, especially for lesser known areas like the African equatorial regions, will help us correct for influences that the ionosphere has on radio signals propagating through it. The International Reference Ionosphere (IRI) model has been accepted as a defector standard for specifying ionospheric parameters across the globe. In this first paper, we present an evaluation of the model's performance over Nsukka, Nigeria. The geographic and geomagnetic coordinates of Nsukka are respectively 6.87°N, 7.38°E and 8.47°N, 81.07°E. The town lies within the Equatorial Anomaly (EA) region, known to be characterized by an F layer depression in electron concentration and lying within approximately ±20° of the magnetic equator.

[3] The Global Positioning System (GPS) is a satellite-based navigation system consisting mainly of a network of transmitter satellites and receivers. Each of the transmitter satellites continually beep out radio signals from space containing their respective 3-D positions and the time of transmission. A receiver on Earth will usually need to receive beeps from at least 4 of the transmitter satellites to be able to use in-built computer programs to compute its (the receiver's) location and current time. Given the GPS satellite orbital design considerations, a total of 24 operational transmitter satellites are required to form an evenly distributed constellation round about the globe to ensure

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that at least 4 of them are visible over any given location on earth.

[4] Dual-frequency receivers are designed to be able to receive signals from the transmitter satellites in two bands (L1 band - 1.57542 GHz, and L2 band – 1.2276 GHz). This makes it possible to include algorithms within such receivers to compute ionospheric delays caused to the propagating radio signals in the form of TEC since the GPS signals transverse the ionosphere carrying signatures of the dynamic medium and thus offer opportunities for ionospheric research [*Bhuyan and Rashmi*, 2007]. In this work, we compare TEC predictions from the IRI model with TEC observations from the AFRL-SCINDA GPS receiver station at Nsukka, Nigeria. We also look forward that this work and future related work on the African region will provide useful information on a proposed TEC modeling over the African continent using the IRI model.

2. Data Sources

2.1. Vertical TEC From the IRI MODEL

[5] The International Reference Ionosphere (IRI) is a working group, jointly sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI), that develops an empirical ionospheric model called the IRI model. The IRI model gives spatial and temporal representations of ionospheric parameters (including TEC) and has been widely regarded as the international standard for specifying ionospheric parameters [*Bilitza*, 2001]. *Bilitza and Reinisch* [2008] also noted that the IRI model has become so widely accepted that a comparison with IRI is often one of the first science tasks by an ionospheric, satellite or rocket team.

[6] The IRI model has 3 topside options for TEC predictions; the NeQuick, the IRI01-cor, and the IRI2001 options. The NeQuick option [*Hochegger et al.*, 2000; *Radicella and Leitinger*, 2001] is default for standard IRI options. In this work, we use the IRI-2007 model with all 3 topside options, and observe as shown in our results that the NeQuick option gave the best topside representation for the region. *Nava et al.* [2008] also observed that the NeQuick option gave an improved performance in predicting the topside ionosphere. In general, the standard IRI options were used, and the upper integration limit for the TEC values was set at 1000 km, a good limit for the IRI model [*Bilitza and McKinnell*, 2011], and to clearly exclude TEC contribution from the plasmasphere, since corresponding data from the GPS equipment also excludes plasmaspheric TEC contribution.

2.2. Vertical TEC From GPS Receivers

[7] GPS data used in this work was obtained from the dual frequency GPS receiver system deployed by AFRL-SCINDA (Air Force Research Laboratory – Scintillation Network Decision Aid). The system is a real-time GPS data acquisition and ionospheric analysis system [*Carrano and Groves*, 2009].

[8] We calibrated the GPS TEC measurements using WinTEC-P, (a software written in C for the LINUX operating system) developed for calibrating SCINDA GPS TEC measurements using a Kalman filter approach by *Carrano et al.* [2009]. The method utilizes the Carpenter-Anderson Plasmaspheric Model [*Carpenter and Anderson*, 1992] to provide an estimation of the line-of-sight plasmaspheric TEC contribution, and then uses the Kalman filter to scale their results to agree with observations. While the Carpenter-Anderson Plasmaspheric Model makes use of empirical models to estimate the electron density in the inner plasmasphere and the location of the plasmaspause, the Kalman filter exploits the difference that exists between the plasmaspheric and ionospheric slant TEC dependences on the elevation angle to distinguish between TEC contributions from the two regions. We also point out that, though at some stage in the method, the plasmaspheric slant TEC term was computed by numerically integrating the electron density along the line of sight from the GPS receiver to each satellite starting from 700 km up to the GPS orbital altitude of 20,200 km, the 700 km was not a final integration limit for the ionospheric TEC contribution since the Kalman filter was consequently used to scale the result. The final integration limit for the ionospheric TEC is not a constant, and depends on the scaling by the Kalman filter. *Carrano et al.* [2009] have more details.

3. Methods and Results

[9] We present in this work an analysis of available GPS-TEC data for year 2010 from the Nsukka SCINDA GPS station as compared with corresponding IRI model values. We computed Correlation Coefficients between the two sets of data, the Root-Mean square Deviations (RMSD) of the IRI-TEC from the GPS-TEC, and the percentage RMSD of the IRI-TEC from the GPS-TEC using equations (1), (2) and (3) respectively.

$$Correlation\,Coefficient = \frac{\sum_i \left(gps_i - \overline{gps_i}\right)\left(iri_i - \overline{iri_i}\right)}{\sqrt{\sum_i \left(gps_i - \overline{gps_i}\right)^2 \sum_i \left(iri_i - \overline{iri_i}\right)^2}} \quad (1)$$

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n} \left(gps_i - iri_i\right)^2}{n}} \quad (2)$$

$$Percentage\,RMSD = \frac{RMSD}{RMS_{gps}} \times 100, \left[where\,RMS_{gps} = \sqrt{\frac{\sum_{i=1}^{n} \left(gps_i\right)^2}{n}} \right] \quad (3)$$

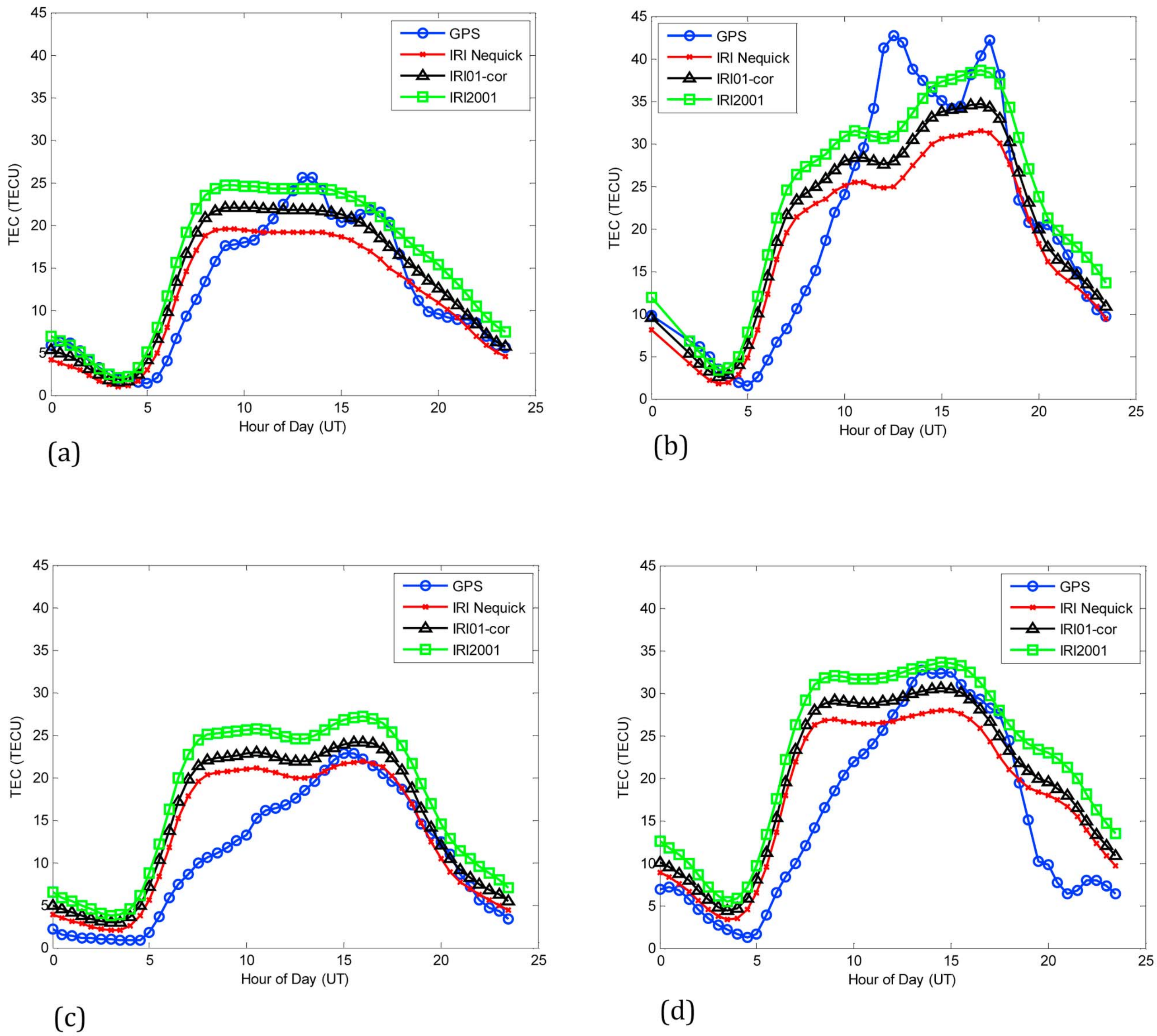

Figure 1. Diurnal TEC graphs for the Nsukka station for (a) 14th January, (b) 5th April, (c) 1st July, and (d) 1st October, 2010. Values are derived from the Nsukka GPS receiver system and from the IRI model (using the 3 different IRI topside options; Nequick, IRI01-cor, and IRI2001).

where gps_i are respective GPS-TEC data, $\overline{gps_i}$ is their mean, iri_i are respective IRI-TEC data, $\overline{iri_i}$ is their mean, and n is the number of them. RMS_{gps} is the root-mean square value for the GPS-TEC data, and the subscripts 'i' denote numerical positions in the data, having integral values from 1 to n.

3.1. Hour to Hour Variations

[10] Figures 1a–1d illustrate how the IRI-TEC values (obtained using all 3 different topside options of the IRI model) compare with corresponding GPS-TEC values for the days of 14th January, 5th April, 1st July, and 1st October 2010 respectively. Each of the 4 days was chosen to represent-days in each quarter of the year, with the first day of each quarter for which there was available all-day round data chosen.

[11] Maximum TEC values were observed during the periods between sunrise and sunset (at about 08:00 UT to 16:00 UT corresponding to 09:00–17:00 local time. Local time in Nigeria is 1 h ahead of Universal Time), an

Table 1a. Correlation Coefficients Between the IRI TEC Values and the GPS TEC Values for the Chosen Four Days of Year 2010

Date (2010)	NeQuick	IRI01-cor	IRI2001
14th January	0.9177	0.9205	0.9158
5th April	0.8877	0.8907	0.8875
1st July	0.9006	0.9024	0.9055
1st October	0.9050	0.9167	0.9070

Table 1b. Root Mean Square Deviations (RMSD) of the IRI TEC Values From the GPS TEC Values for the Four Chosen Days Of Year 2010

	RMSD (TECU)			Percentage RMSD (%)		
Date (2010)	NeQuick	IRI01-cor	IRI2001	NeQuick	IRI01-cor	IRI2001
14th January	3.0975	3.2625	4.6645	21.2568	22.3891	32.0104
5th April	6.8764	6.3106	6.9558	27.7466	25.4633	28.0666
1st July	4.0821	5.2383	7.2421	31.0629	39.8608	55.1092
1st October	6.2709	7.3181	9.9947	33.5170	39.1144	53.4204

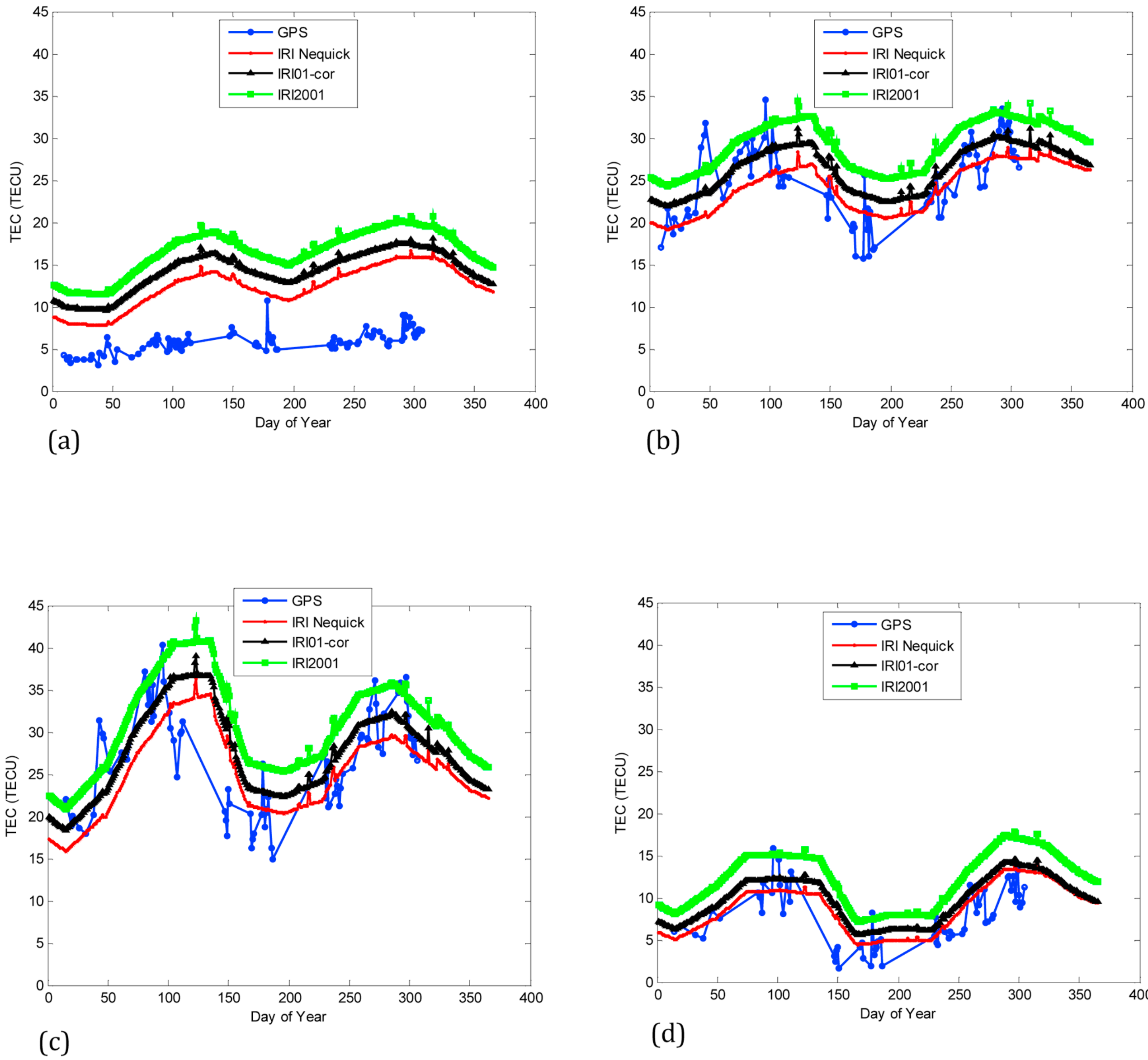

Figure 2. Annual TEC graphs for the Nsukka station for (a) 06 h00 UT, (b) 11 h00 UT, (c) 17 h00 UT, and (d) 23 h00 UT, year 2010. Values are derived from the Nsukka GPS receiver system and from the IRI model (using the 3 different IRI topside options; Nequick, IRI01-cor, and IRI2001).

Table 2a. Correlation Coefficients Between the IRI TEC Values and the GPS TEC Values, for All Hours of a Day

Hour of Day (UT)	NeQuick	IRI01-cor	IRI2001
00 h00	0.6382	0.6669	0.6719
01 h00	0.6672	0.6858	0.6869
02 h00	0.6467	0.6659	0.6692
03 h00	0.5718	0.5729	0.5782
04 h00	0.2336	0.2063	0.2096
05 h00	0.1971	0.1870	0.1864
06 h00	0.7013	0.6925	0.6909
07 h00	0.6043	0.5859	0.5793
08 h00	0.6232	0.6350	0.6273
09 h00	0.6042	0.6411	0.6320
10 h00	0.6275	0.6682	0.6582
11 h00	0.7036	0.7461	0.7387
12 h00	0.6928	0.7371	0.7345
13 h00	0.7124	0.7484	0.7463
14 h00	0.7542	0.7793	0.7753
15 h00	0.7649	0.7839	0.7785
16 h00	0.7107	0.7303	0.7237
17 h00	0.6610	0.6857	0.6797
18 h00	0.7104	0.7272	0.7249
19 h00	0.6611	0.6742	0.6716
20 h00	0.5803	0.5904	0.5879
21 h00	0.6574	0.6591	0.6553
22 h00	0.7473	0.7484	0.7448
23 h00	0.7698	0.7772	0.7776

affirmation that the solar radiation is a major cause of the ionization process in the ionosphere. Minimum TEC values were observed at periods between 03:00 and 06:00 local time (toward the start of sunrise) corresponding to the period when the solar ionization activity caused by the previous sunrise is getting minimal. The observations generally agree with well known ionospheric theories on ionization, and with similar work that has been done for the region by *Adewale et al.* [2011], *Okoh et al.* [2011], and *Rabiu et al.* [2011].

[12] Correlation coefficients between the IRI-TEC values and the GPS-TEC values for the four days are shown in Table 1a, while Table 1b contains information on root-mean square deviations (RMSD) of the IRI-TEC values from the GPS-TEC values for the four days. Table 1a shows very good correlation (above 0.88) for all the 3 topside options used, and for all the four days. The RMSD of the IRI-TEC from the GPS-TEC were also generally good. Using the IRI model with the NeQuick topside option presented the best scenario with a maximum of ~33.5% TEC deviation, while with the IRI2001 topside option presented the worst scenario (maximum of ~55.1% TEC deviation). On the least, we expect some of these TEC deviations from the IRI because the 1000 Km upper integration limit chosen for the IRI predictions are likely not to always coincide exactly with the upper integration limit for the AFRL-SCINDA GPS calibration algorithm. As mentioned earlier (Section 2.2), the upper integration limit for the ionospheric TEC contribution in this method is not a constant, and depends on the scaling results of the Kalman filter for each observation, tendencies are that the limits will not always correspond to 1000 km as we have used in the IRI model, and so a likely source of the slight discrepancies noted between the IRI-TEC and GPS-TEC values.

[13] Another possible reason for the departures is in the relatively small amount of data from the region considered in developing the model. Given that the IRI model is data-based, the accuracy of the model in a specific region depends on the availability of reliable data for the region. *Bilitza and Reinisch* [2008] list the paucity of ionospheric data over the African Equatorial region as a factor most likely responsible for the lesser accuracies of the IRI predictions over the region.

3.2. Day to Day Variations

[14] We illustrate in Figures 2a–2d how the IRI-TEC values compare with corresponding GPS-TEC values for the following hours of the year taken throughout year 2010 for periods for which there was GPS data; 06:00 UT, 11:00 UT, 17:00 UT and 23:00 UT respectively. These four hour times were chosen to represent local morning, mid-day, evening and mid-night. Table 2a shows correlation coefficients between the IRI-TEC and the GPS-TEC values for each hour, while Table 2b show root-mean square deviations of the IRI-TEC from the GPS-TEC values for the hours. For each hour, the correlation coefficients and root-mean square deviations were computed using available TEC data for that hour running through the days of the year.

[15] There was also a generally good correlation between the IRI and GPS TEC values except for periods around

Table 2b. Root Mean Square Deviations (RMSD) of the IRI TEC Values From the GPS TEC Values, for All Hours of a Day

Time (UT)	RMSD (TECU)			Percentage RMSD (%)		
	NeQuick	IRI01-cor	IRI2001	NeQuick	IRI01-cor	IRI2001
00 h00	2.4912	2.2899	3.2297	33.5823	30.8684	43.5374
01 h00	2.1275	2.5182	4.0523	34.4830	40.8165	65.6827
02 h00	1.5771	1.8301	2.9616	33.8830	39.3191	63.6277
03 h00	1.2914	1.2736	1.8378	39.4347	38.8902	56.1202
04 h00	1.3396	1.9466	2.7454	60.0503	87.2613	123.0708
05 h00	3.9893	5.4258	6.9377	191.5542	260.5286	333.1245
06 h00	7.0199	8.8446	11.2296	116.8931	147.2765	186.9920
07 h00	9.6737	11.3165	14.2220	91.3731	106.8905	134.3340
08 h00	8.5471	10.0633	13.0659	56.3065	66.2947	86.0751
09 h00	5.3770	6.9731	9.8070	27.2257	35.3078	49.6568
10 h00	3.4933	4.7913	7.3327	15.0827	20.6871	31.6598
11 h00	3.3937	3.3323	5.1980	13.2142	12.9752	20.2400
12 h00	5.1279	3.8347	4.1122	18.3258	13.7043	14.6961
13 h00	5.8453	4.4193	4.3489	19.8075	14.9754	14.7369
14 h00	5.4784	4.3693	4.9570	18.1698	14.4913	16.4405
15 h00	4.8586	4.2233	5.5526	16.2026	14.0839	18.5171
16 h00	4.8652	4.4821	6.0660	16.5607	15.2567	20.6483
17 h00	4.7616	4.7560	6.7032	17.2325	17.2121	24.2591
18 h00	4.0530	5.2184	8.0729	17.7020	22.7922	35.2595
19 h00	4.7246	6.1235	9.2886	27.8283	36.0679	54.7106
20 h00	4.8150	5.8561	8.9032	36.3096	44.1609	67.1390
21 h00	4.1967	5.0193	7.8463	36.6767	43.8653	68.5714
22 h00	3.2297	3.9920	6.5415	32.1075	39.6856	65.0304
23 h00	2.5024	3.1216	5.2709	29.0321	36.2154	61.1508

04:00 UT and 08:00 UT where the correlations sometimes dropped to below 0.5 and the deviations sometimes rose to above 100%. The pronounced departures at these periods are also expected knowing that the IRI is a model that compares well with mean or median values; during these periods we have the steepest slopes in the diurnal TEC plots as deviations from proceeding TEC values are usually higher then, thereby increasing the uncertainty level in the model predictions at those periods. Similar work done by *Chauhan and Singh* [2010] and *Zhang et al.* [2006] also suggest the greatest departures of the IRI-TEC from the GPS-TEC at those periods.

[16] Seasons of a year arise mainly because of the tilt of the Earth's rotational axis relative to its orbital plane combined with its revolution round the sun. Since Nsukka is located near the geographical equator, we prefer to speak of the seasons in terms of solstices and equinoxes rather than the summer solstice, winter solstice, autumn equinox and spring equinox; the tropics do not experience significant levels of variations in the sun's intensity between the winter and the summer solstices and between the equinoxes like in the temperate/polar regions, remarkable differences are noticeable between the solstices (when the Sun is away from the equator, on either side of it) and the equinoxes (when the sun is overhead the equator). Figures 2a–2d show, as expected, that the TEC values are highest during the equinoxes (at around day numbers 100 and 280 of the year) and lowest during the solstices (at around day numbers 10 and 190 of the year).

4. Conclusion

[17] The results show that the IRI TEC values generally compared well with the GPS TEC values, with correlation coefficients as good as about 0.9, and root-mean square deviations generally around 20–50% for diurnal comparisons. Diurnal comparisons were generally better than the day to day comparisons since the IRI model is known to compare well with mean or median values. The worst scenarios were around 04 h00 to 08 h00 UT, corresponding to periods when the TEC gradients are highest.

[18] Data used in this work was for year 2010 (a year of low solar activity), we have proposed doing similar work for the region to ascertain if similar variations will be noted during years of high and moderate solar activity, and when done, will enhance the practical understanding initiated in this work.

[19] Since a major interest in this work is to establish a rationale on how to use the IRI model to develop a TEC map for the African region, we suggest that similar work be done for other GPS stations across the continent, and more attention be paid to note if the level of inconsistencies are similar to those noted in this work.

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