Validation of University of New Brunswick Ionospheric Modeling Technique with ionosonde TEC estimation over South Africa

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Abstract

For more than a decade, ionospheric research over South Africa has been carried out using data from ionosondes geographically located at Madimbo (28.38°S, 30.88°E), Grahamstown (33.32°S, 26.50°E), and Louisvale (28.51°S, 21.24°E). The objective has been modelling the bottomside ionospheric characteristics using neural networks. The use of Global Navigation Satellite System (GNSS) data is described as a new technique to monitor the dynamics and variations of the ionosphere over South Africa, with possible future application in high frequency radio communication. For this task, the University of New Brunswick Ionospheric Modelling Technique (UNB-IMT) was applied to compute midday (10:00 UT) GNSS-derived total electron content (GTEC). GTEC values were computed using GNSS data for stations located near ionosondes for the years 2002 and 2005 near solar maximum and minimum, respectively. The GTEC was compared with the midday ionosonde-derived TEC (ITEC) measurements to validate the UNB-IMT results. It was found that the variation trends of GTEC and ITEC over all stations are in good agreement and show a pronounced seasonal variation for the period near solar maximum, with maximum values ($\sim$80 TECU) around autumn and spring equinoxes, and minimum values ($\sim$22 TECU) around winter and summer. Furthermore, the residual $\Delta TEC = GTEC - ITEC$ was computed. It was evident that ΔTEC, which is believed to correspond to plasmaspheric electron content, showed a pronounced seasonal variation with maximum values ($\sim$20 TECU) around equinoxes and minimum ($\sim$5 TECU) around winter near solar maximum. The equivalent ionospheric and total slab thicknesses were also computed and comprehensively discussed. The results verified the use of UNB-IMT as one of the tools for future ionospheric TEC research over South Africa.

1. Introduction

For more than a decade, ionospheric research over South Africa has been carried out using data from three ionospheric sounders located at Grahamstown (33.32°S, 26.50°E), Louisvale (28.51°S, 21.24°E), and Madimbo (28.38°S, 30.88°E). These three ionosondes are all digital pulse sounders, manufactured by the University of Massachusetts Lowell Center for Atmospheric Research (Reinisch, 1996). The objective has been modelling bottomside ionospheric parameters using neural networks (e.g., [Williscroft and Poole, 1996], [McKinnell and Poole, 2000] and [Poole and McKinnell, 2000]; [Oyeyemi and Poole, 2004] and [McKinnell and Poole, 2004]). Recently, efforts have been undertaken to use Global Navigation Satellite System (GNSS) as a new technique to monitor the dynamics and variations of the ionosphere over South Africa ([Cilliers et al., 2004], [Ngcobo et al., 2005], [Moeketsi et al., 2007a], [Moeketsi et al., 2007b], [Opperman et al., 2007], [McKinnell et al., 2007] and [Moeketsi, 2008]). The dual frequency (L1 = 1572.42 MHz and L2 = 1227.60 MHz) signals transmitted by GNSS, and received by the worldwide network of GPS receivers, can be used in a technique to determine the high resolution spatial and temporal ionospheric total electron content (TEC) at regional and global level (e.g., [Klobuchar, 1991], [Komjathy and Langley, 1996], [Jakowski, 1996], [Komjathy, 1997] and [Mannucci et al., 1998]). This is possibly due to the dispersive nature of the ionospheric medium (e.g., Ratcliffe, 1959). The signals from GNSS experience time delays when traversing the ionosphere due to the interaction with free electron gas. The net effect of this delay is directly proportional to the integrated electron density (TEC) along the signal path from the position of the satellite (∼22,000 km) to the receiver on Earth (e.g., [Klobuchar, 1991] and [Langley, 1996]). The unit for TEC used consistently in this work is TECU (1 TECU = 10^{16} electrons m^{-2}). Decades of ionospheric research showed that TEC is highly variable and depends on several factors such as local time, geographical location, season and solar cycle (e.g., [Jakowski, 1996], [Jakowski et al., 1999], [Tsurutani et al., 2005], [Mannucci et al., 2005], [Fedrizzi et al., 2005], [Moeketsi et al., 2007a], [Moeketsi et al., 2007b] and [Moeketsi, 2008]). Recently, (Jakowski et al., 2001) and (Jakowski et al., 2002) illustrated that TEC monitoring using the GNSS network can contribute to space weather monitoring. On the other hand, Lui et al. (2007) used unique CHAMP satellite data to investigate effects of solar flares not only on the ionosphere, but also on the thermosphere and they reported important temporal and latitudinal differences between the two components, which is crucial for improving space weather models of the upper atmosphere.

A new technique has been proposed by Reinisch and Huang (2001) to estimate the topside ionospheric electron density profile from ground-based ionosonde measurements. This technique provides another tool to determine TEC by calculating the integral from 0 to ∼1000 km over the entire ionospheric electron density profile. However, it is crucial to note that this technique has limitations in terms of geographical location of ionospheric sounders and spatial coverage in determining TEC. The GNSS technique provides more detailed information and is not limited in geographical and spatial coverage and, therefore, should complement the ionosondes but not replace them. It has been shown recently that a comparison of ionosonde-derived TEC (ITEC) and GPS derived TEC (GTEC) and other techniques (e.g., Incoherent Scatter Radar, Geostationary Satellite Beacons, and TOPEX) at lower and mid-latitudes show, in general, a very good level of agreement ([Reinisch and Huang, 2001], [Belehaki and Tsagouri, 2002], [Belehaki et al., 2003a], [Belehaki et al., 2003b], [Zhang et al., 2006] and [McKinnell et al., 2007]).

In this paper, we compare midday GTEC derived using the University of New Brunswick Ionospheric Modelling Technique (UNB-IMT) (Komjathy, 1997) with ITEC measurements from the three ionosondes in South Africa. The study is performed for two selected periods during the descending phase of solar cycle 23; the year 2002 for near solar maximum, and 2005 for near solar minimum conditions. The ITEC values are derived from ionograms using the technique described in Reinisch and Huang (2001). The aim of this study is to investigate midday TEC variability over South Africa during different periods of solar cycle 23 and further to validate UNB-IMT TEC results using ITEC measurements as one of the tools to be used for future related ionospheric physics research and application over South Africa.

2. The UNB Ionospheric Modelling Technique

The UNB-IMT Unix compatible version was developed during 1997, in the department of Geodesy and Geomantic Engineering at the University of New Brunswick, to compute global and regional TEC from GNSS observables at both the L1 and L2 frequencies in order to provide ionospheric corrections to communication, surveillance, and navigation systems operating at a single frequency ([Komjathy and Langley, 1996], [Komjathy, 1997] and [Komjathy et al., 1998]). Fedrizzi et al. (2005) also used the same model to study TEC variability associated with geomagnetic storm activity over locations in the South American Sector. Efforts were undertaken within the Space Geodesy Programme of the Hartebeesthoek Radio Astronomy Observatory (HartRAO) to modify the UNIX version of the UNB Model to compile and execute on a Linux platform in order to compute TEC over South Africa ([Ngcobo et al., 2005], [Moeketsi et al., 2007a], [Moeketsi et al., 2007b] and [Moeketsi, 2008]). Most recently, (Moeketsi et al., 2007a) and (Moeketsi et al., 2007b) and Moeketsi (2008) adopted the same model to study ionospheric TEC response to solar flares over South Africa during different epochs of solar cycle 23. It has been shown that TEC results from this model can be used for space weather monitoring over South Africa.

The UNB-IMT technique uses the single-layer ionospheric model to compute TEC from dual frequency GPS receivers, according to the following observation equation (Komjathy, 1997):

$$F_r^s(t_k) = M(e_r^s)[a_{0,r}(t_k) + a_{1,r}(t_k)d\lambda_r + a_{2,r}(t_k)d\varphi_r] + b_r + b^s \tag{1}$$

where $F_r^s(t_k)$represents the line-of-sight L1–L2 phase-leveled measurements obtained by receiver r observing satellite s at epoch t_k. $M(e_r^s)$is the mapping function, e_r^srepresents the satellite elevation angle, $a_{0,r}$, $a_{1,r}$, and $a_{2,r}$ are stochastic parameters for spatial linear approximation of TEC to be estimated for receiver r and assuming a first-order Gauss-Markov stochastic process (Gail et al., 1993). Furthermore, $d\lambda_r=\lambda_r-\lambda_0$ is the difference between a sub-ionospheric point and the mean longitude of the Sun, $d\varphi_r = \varphi_r - \varphi_0$ is the difference between the geomagnetic latitude of the sub-ionospheric point and the geomagnetic latitude of the station, b_r and b^s refers to the receiver and satellite instrumental biases, respectively. For further information on how these biases are estimated, see Komjathy (1997).

The PhaseEdit version 2.2 automatic data editing program was used to detect bad points and cycle slips, as well as repair the cycle slips and adjust phase ambiguities using the undifferenced GPS data. The program takes advantage of the high precision dual frequency pseudo range measurements to adjust L1 and L2 by an integer number of cycles to agree with the pseudo range measurements (Fedrizzi et al., 2005). The elevation cutoff angle was set to 10°.

Furthermore, the UNB-IMT algorithm uses the standard geometric mapping function expressed as (Mannucci et al., 1993)

$$M(e_r^s) = \left[1 - \frac{r_E^2 \cos^2 e_r^s}{(r_E + h)^2}\right]^{-\frac{1}{2}}. \tag{2}$$

Here, r_E is the mean radius of the Earth and h is the mean value for the assumed height of the thin spherical ionospheric shell, located at a height of 400 km (Komjathy, 1997). Eq. (2) computes the secant of the zenith angle of the signal geometry ray path at the ionospheric pierce point and projects the line-of-sight measurements to the vertical of the sub-ionospheric point. It is crucial to note that recent studies comparing different TEC mapping techniques reported an improvement in accuracy of the determination of TEC in the dayside ionosphere compared with the thin shell method ([Meggs et al., 2004] and [Meggs and Mitchell, 2006]).

As a result of the ionospheric dependence on solar radiation and the geomagnetic field, the model uses a solar-geomagnetic reference frame to compute TEC at each grid point. TEC values change at a slower rate in this reference frame compared to an Earth-fixed one. The ionospheric model was evaluated for the four closest stations to a grid node at which a TEC value is computed. Consequently, the inverse-distance-squared weighted averages of the individual TEC data values for the four stations were computed. The closer a particular grid node is to a GPS station, the more weight was placed on the TEC values computed by evaluating the temporal and spatial variation of the ionosphere above the particular station.

3. Observations and data analysis

The data sampled at 30 s from 16 South African dual frequency GNSS receivers were used in this study as an input to the UNB-IMT code described in Section 2. The stations' geographical coordinates and geomagnetic latitudes are listed in Table 1 and depicted in Fig. 1. The International GNSS data used are obtained from the HartRAO data server ftp://geoid.hartrao.ac.za and can also be obtained from ftp://lox.ucsd.edu/pub/rinex (see also Combrinck et al., 2003), while the South Africa CDSM Trignet data were obtained from http://www.trignet.co.za. It was ensured that the quality of the GPS data was checked for all stations using the UNAVCO Translate/Edit/Quality Check (TEQC) software. The software module "EditObs" developed locally (Ngcobo et al., 2005) was used to extract the GPS observables used by UNB code from the Receiver Independent Exchange format (RINEX) GPS observation file. Using the technique described in Section 2, the midday TEC values for the years 2002 and 2005 were determined for all GNSS stations located near the ionosondes. It is crucial to note that there are days in which GNSS data were not recorded particularly during this first quarter of the year 2002. As consequence, this resulted in gaps in the computed GTEC data.

Table 1.

Geographical coordinates and geomagnetic latitudes of southern Africa ionosondes and dual frequency GNSS receivers used in this work.

Station name/code	Geographical latitude (°)	Geographical longitude (°)	Geomagnetic latitude (°)
South African ionosondes			
Grahamstown	−33.32	26.50	−34.30
Louisvale	−28.51	21.24	−28.53

Station name/code	Geographical latitude (°)	Geographical longitude (°)	Geomagnetic latitude (°)
Madimbo	−22.38	30.88	−24.28
South African GNSS receivers			
HARB	−25.89	27.71	−27.13
HRAO	−29.89	27.69	−27.13
EMLO	−26.30	29.59	−27.87
PMBG	−29.36	30.23	−30.98
PBWA	−23.57	31.08	−25.46
PTBG	−23.55	29.28	−25.12
ERAS	−23.41	27.41	−24.65
KMAN	−27.27	23.26	−27.70
UPTN	−28.24	21.15	−28.27
SBOK	−29.40	17.52	−28.76
DEAR	−30.39	23.59	−30.81
SUTH	−32.38	20.81	−32.26
SIMO	−34.19	18.44	−33.61
GFNT	−32.15	24.32	−32.66
PELB	−33.98	25.61	−34.68
ELDN	−33.02	27.49	−34.08

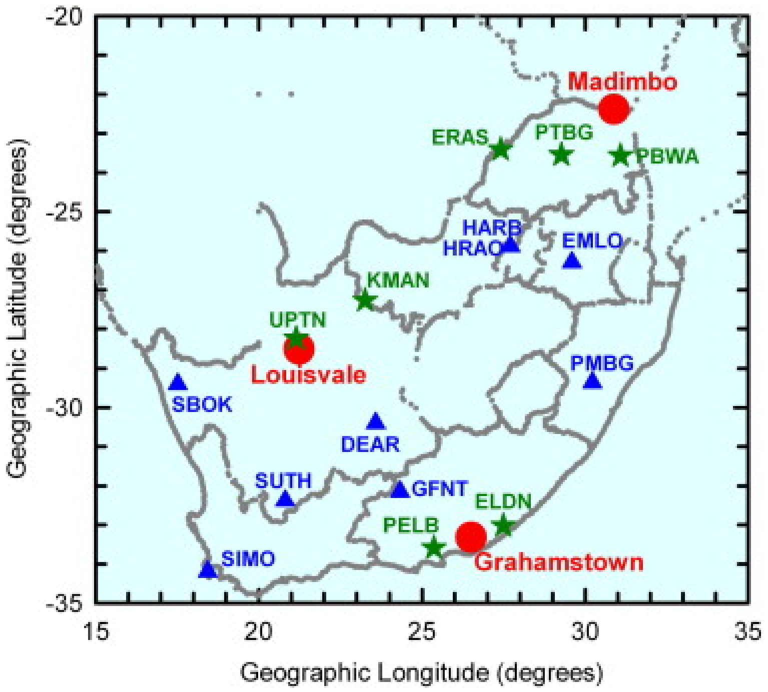

Fig. 1. Geographic locations of Madimbo, Louisvale, and Grahamstown (red cycle) and South African GNSS network (blue triangles and green stars) of dual frequency receivers used during data processing in this work. The green stars denote the selected long time data record GNSS receivers located near ionosondes used for the purpose of this study. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The electron density profiles determined from the Madimbo, Grahamstown, and Louisvale ionosonde measurements over South Africa were used to determine ITEC by applying the technique described in Reinisch and Huang, 2001. The ionosonde stations geographic coordinates and geomagnetic latitudes are listed in Table 1 and shown in Fig. 1. The electron density profile up to 1000 km is derived from a combination of the inverted bottomside ionograms and a modelled topside profile (Reinisch and Huang, 2001). All three ionosonde measurements have a time resolution of at least 30 min, and were automatically scaled using the University of Massachusetts Lowell ARTIST scaling software (McKinnell et al., 2007). To ensure data quality assurance, all recorded ionograms used for this work were manually edited for quality control before obtaining daily hourly ITEC data from ionograms. The midday ITEC values for years 2002 and 2005 were determined for all three ionosonde stations. There are some days in which ionogram data were not recorded, particularly for the period of near solar maximum conditions (2002) and this resulted in gaps in the ITEC data.

4. Results and discussions

Two years (2002 and 2005) corresponding to the descending phase of solar cycle 23 were selected for this work, which compared to the local midday GTEC derived using the UNB-IMT algorithm with the ITEC measurements determined from the Madimbo, Grahamstown, and Louisvale ionograms observed over South Africa. The results are discussed in this section.

4.1. Comparison of midday GTEC with ITEC measurements near solar maximum

Fig. 2(a)–(c) depict a comparison of midday GTEC computed using UNB-IMT with ITEC measurements over Madimbo, Grahamstown, and Louisvale ionosondes located in South Africa, for the period near solar maximum. Panels show the TEC comparison computed from:

(a) Phalaborwa (PBWA), Pietersburg (PTBG), and Erasmia (ERAS) GNSS stations located near the Madimbo ionosonde,

(b) Port Elizabeth (PELB) and East London (ELDN) GNSS stations located near the Grahamstown ionosonde, and

(c) Kuruman (KMAN) and Upington (UPTN) GNSS stations near the Louisvale ionosonde.

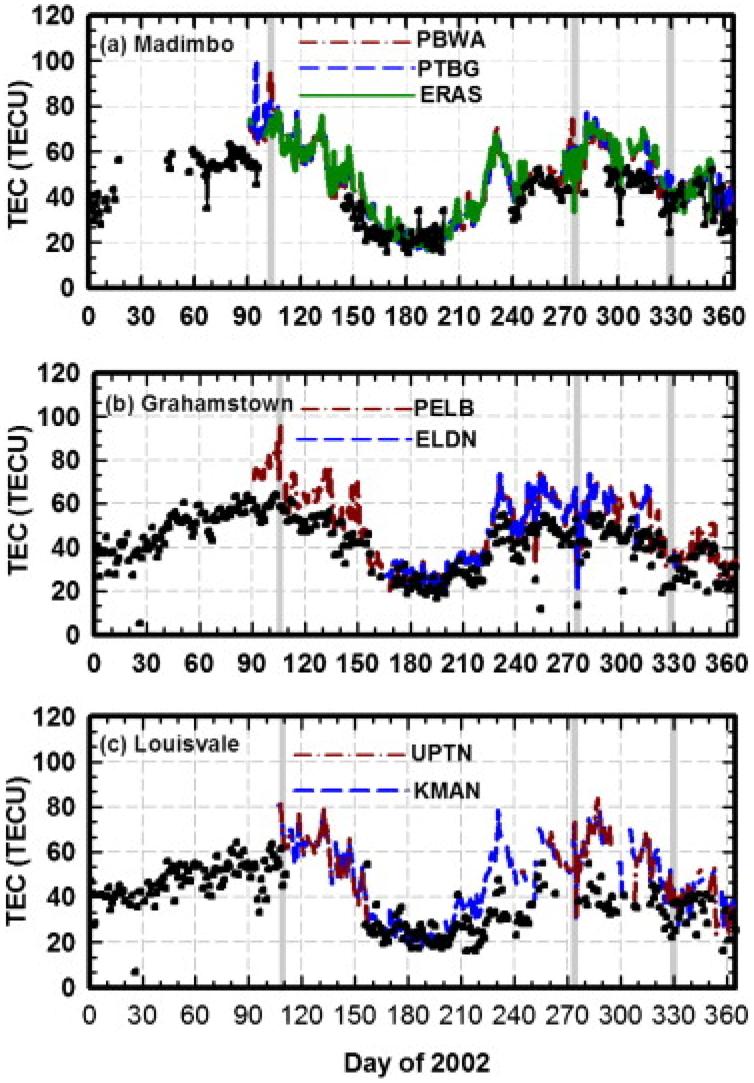

Fig. 2. Comparison of midday TEC computed with UNB model with ionosonde TEC measurements over South Africa for the period near solar maximum. Panels show TEC comparison computed from: (a) PBWA (dash-dot-dash line), PTBG (dashed line) and ERAS (solid line) GPS stations in the vicinity of Madimbo ionosonde location, (b) PELB and ELDN GPS stations located in vicinity of Grahamstown ionosonde, and (c) KMAN and UPTN stations located near Louisvale ionosonde. The ionosonde TEC measurements are denoted by black scatter points.

The midday GTEC values are computed from Day 91 of 2002 due to a lack of GPS data recorded during early 2002, while ITEC values were determined for the whole period, except for the days were the ionogram data were not recorded. However, it is inferred from the panels that the variation trend of GTEC and ITEC over all stations are generally in good agreement and show pronounced seasonal variations with maximum values (~80 TECU) around autumn and spring equinoxes and minimum values (~22 TECU) around winter and summer. Of particular interest would be the significant TEC depletions and enhancement observed from both techniques over all stations as shown by shaded-grey bands. Analysis and discussion on these observations is beyond the scope of this study, and require high temporal resolution data.

4.2. Comparison of midday GTEC with ITEC measurements near solar minimum

Fig. 3(a)–(c) is similar to Fig. 2(a)–(c), but is shown for the period 2005 near solar minimum conditions. It is clear that the variation trend of GTEC and ITEC are generally in good agreement. A less pronounced seasonal variation of TEC is evident from both techniques with maximum values (∼30 TECU) around autumn and spring equinoxes and minimum values (∼10 TECU) around winter and summer as compared to the year 2002 for the solar maximum as discussed in Section 4.1. Of interest could be the enhanced TEC spikes observed from both techniques over all stations as shown by shaded-grey bands. To investigate the latter is beyond the scope of this study and should be left for future works using high temporal resolution data sets as noted in Section 4.1.

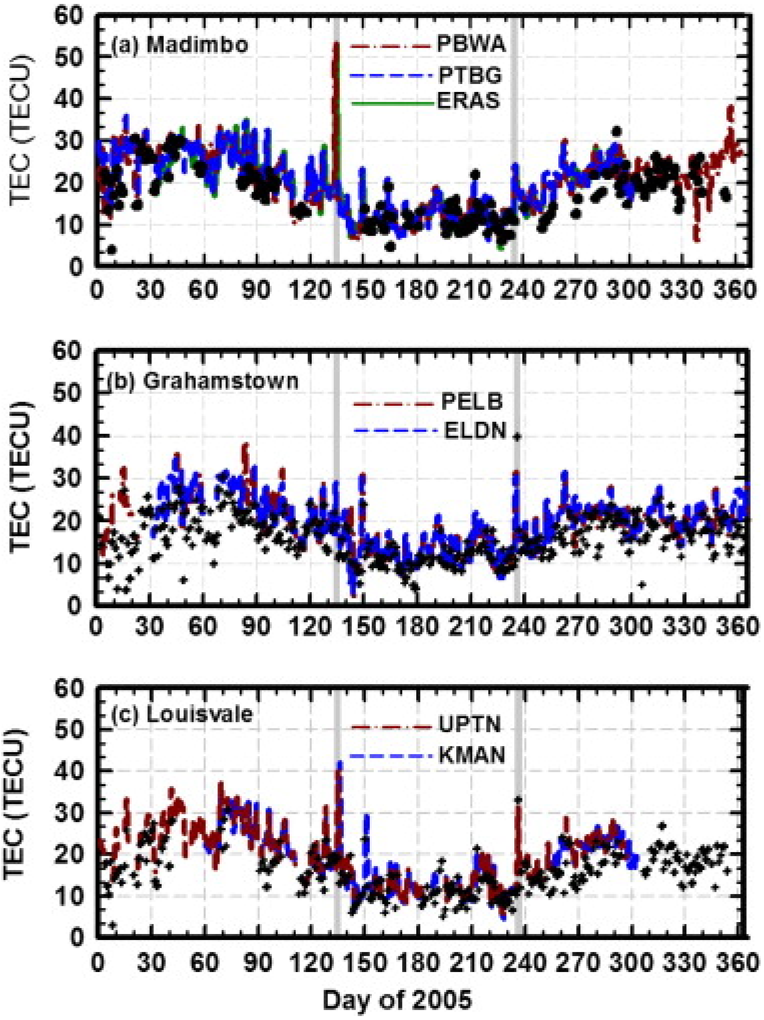

Fig. 3. Similar to Fig. 2, but shown for 2005 near solar minimum conditions.

.3. The difference between midday GTEC and ITEC

In order to compute the difference between midday GTEC and ITEC for both the period 2002 near solar maximum and the period 2005 near solar minimum, the mean GTEC = $\frac{1}{n}\sum_{i=1}^{n}\mathrm{TEC}_i$(where $i = 1,\ldots n$, represents the number of GNSS stations used) was calculated for the selected GNSS station near each ionosonde station for the days where data were available. For illustration, Fig. 4 shows the scatter plot of midday average GTEC against the corresponding ITEC values over Madimbo, Grahamstown and Louisvale stations for the year 2002 near solar maximum (panels (a)–(c)) and the year 2005 near solar minimum (panels (d)–(e)). In general, the scatter plots show a good correlation between both techniques over all sites. The lines drawn correspond to the best-fit line. However, a closer examination of the intercept of the best-fit lines reveals that the midday GTEC values exceed those of ITEC by ~1.96 TECU, ~1.26 TECU, and ~0.32 TECU over Madimbo, Grahamstown, and Louisvale, respectively, for the year 2002 near solar maximum. For the year 2005 near solar minimum, the midday GTEC values exceed those from ITEC by ~0.58 TECU, ~1.18 TECU, and ~1.88 TECU over Madimbo, Grahamstown, and Louisvale, respectively. The latter values, particularly over Grahamstown and Madimbo (~1.18 TECU and ~0.58 TECU), are significantly lower than the ~3.6 TECU recently reported by McKinnell et al. (2007). A reason could be that for this study we only considered the midday (10:00 UT) TEC values from both techniques while the McKinnell et al. (2007) study used diurnal TEC data from March to June 2005. As is reported in Belehaki and Kersley (2006), the interpretation of the small intercepts found in the daytime are difficult to explain. However, this could be attributed to inaccuracies by the application of topside extrapolation method with constant scale height in calculation of ITEC parameters. Future studies are needed to investigate the latter. Nevertheless, these results are comparable with related studies performed using data in the Northern Hemisphere ([Lunt et al., 1999], [Belehaki et al., 2003b] and [Zhang et al., 2006]).

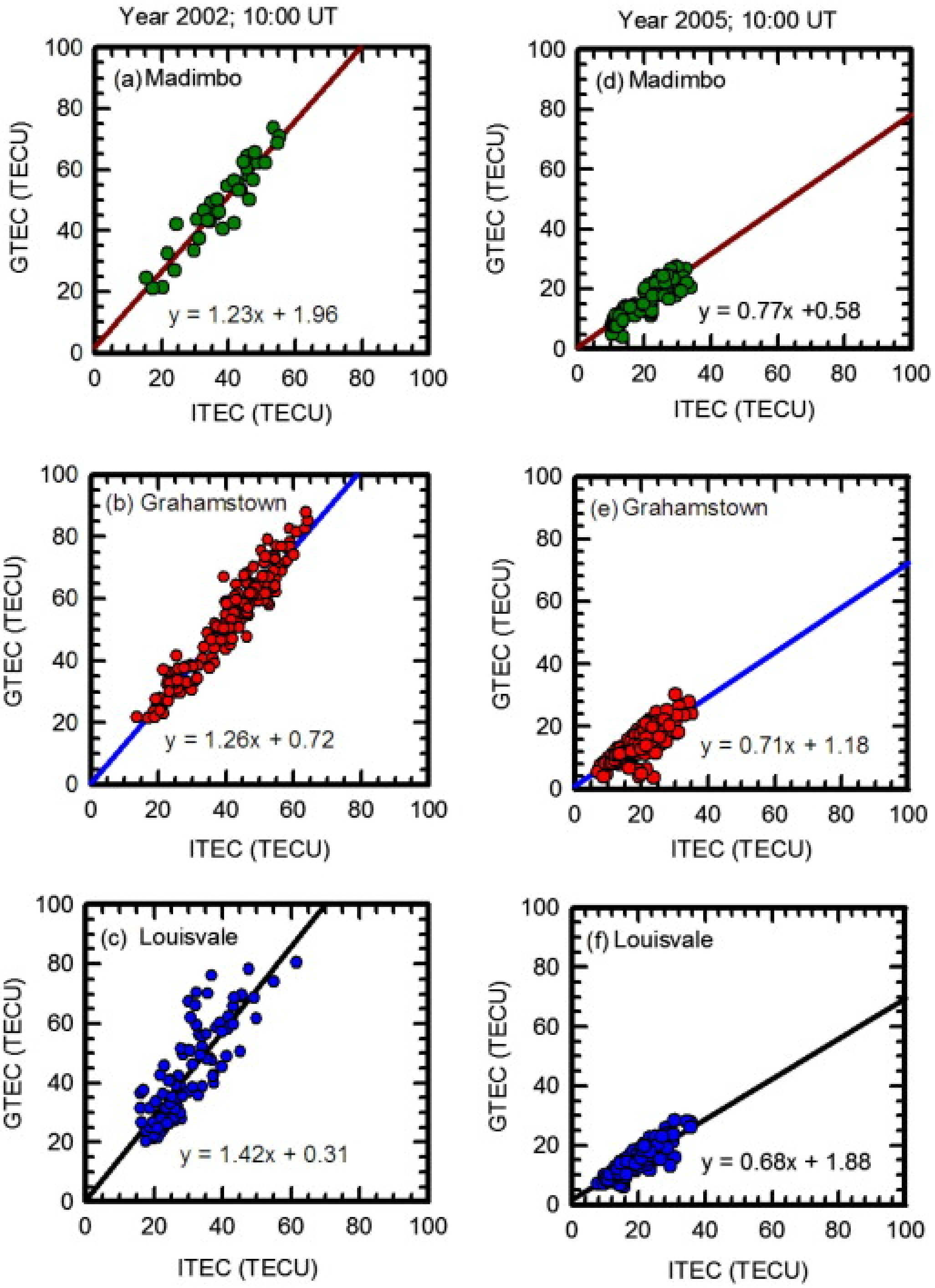

Fig. 4. The scatter plot of midday (10:00 UT) GTEC against the corresponding ITEC over Madimbo, Grahamstown, and Louisvale stations. (a), (b), and (c) correspond to the period 2002 near solar maximum and (d), (e), and (f) represent period 2005 near solar minimum. The lines drawn correspond to the best-fit line.

Furthermore, the residual ΔTEC = GTEC − ITEC, which corresponds to plasmaspheric electron content (e.g., [Reinisch and Huang, 2001], [Belehaki et al., 2003a] and [Belehaki et al., 2003b]), was computed over (a) Madimbo, (b) Grahamstown, and (c) Louisvale stations and is shown in Fig. 5 and

Fig. 6 for the year 2002 near solar maximum, and the year 2005 near solar minimum conditions. It is evident that midday ΔTEC trends over all stations show pronounced seasonal variations for the period around 2002 with large values (~20 TECU) around autumn and spring equinoxes and small values (~ 4 TECU) around winter and summer. For the year 2005, plasmaspheric electron content is highly variable with a minimum value of ~2 TECU and a maximum value of ~10 TECU over all stations. The seasonal variation is difficult to trace considering plasmaspheric electron content trends. This could be an indication of the reduction of the seasonal variation trend of the plasmaspheric electron content towards solar minimum conditions. On the other hand, the contribution of inaccuracies in determining ΔTEC associated with both techniques cannot be ruled out and require further investigations. However, noting that there was also a lack of data recorded for some days by both techniques, more data are required to further investigate the dynamics and variations of plasmaspheric electron content over South Africa so that its contribution to TEC can be understood.

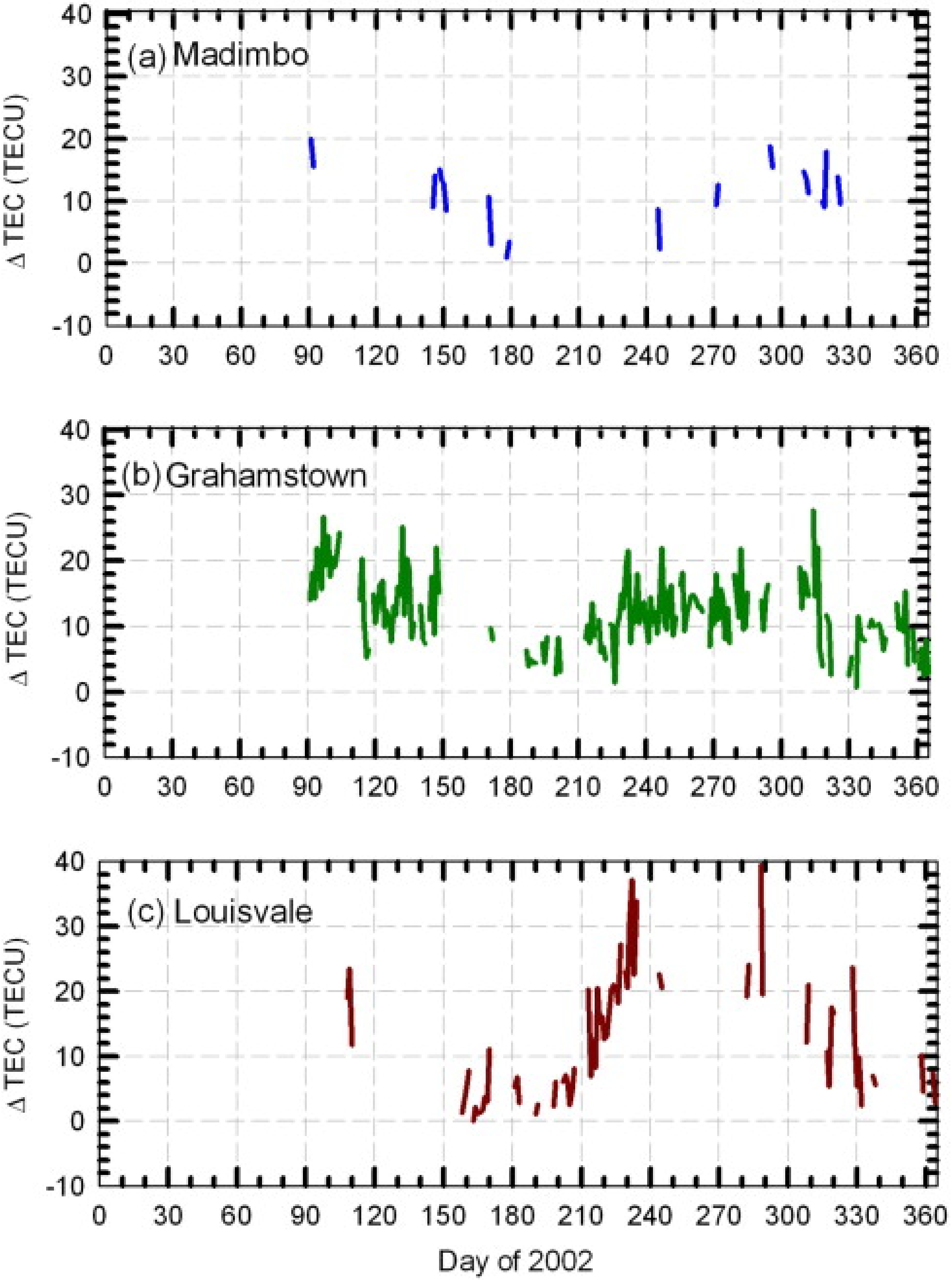

Fig. 5. Computed difference ΔTEC between mean GPS TEC and Ionosonde TEC measurements over (a) Madimbo, (b) Grahamstown, and (c) Louisvale for period 2002 near solar maximum conditions.

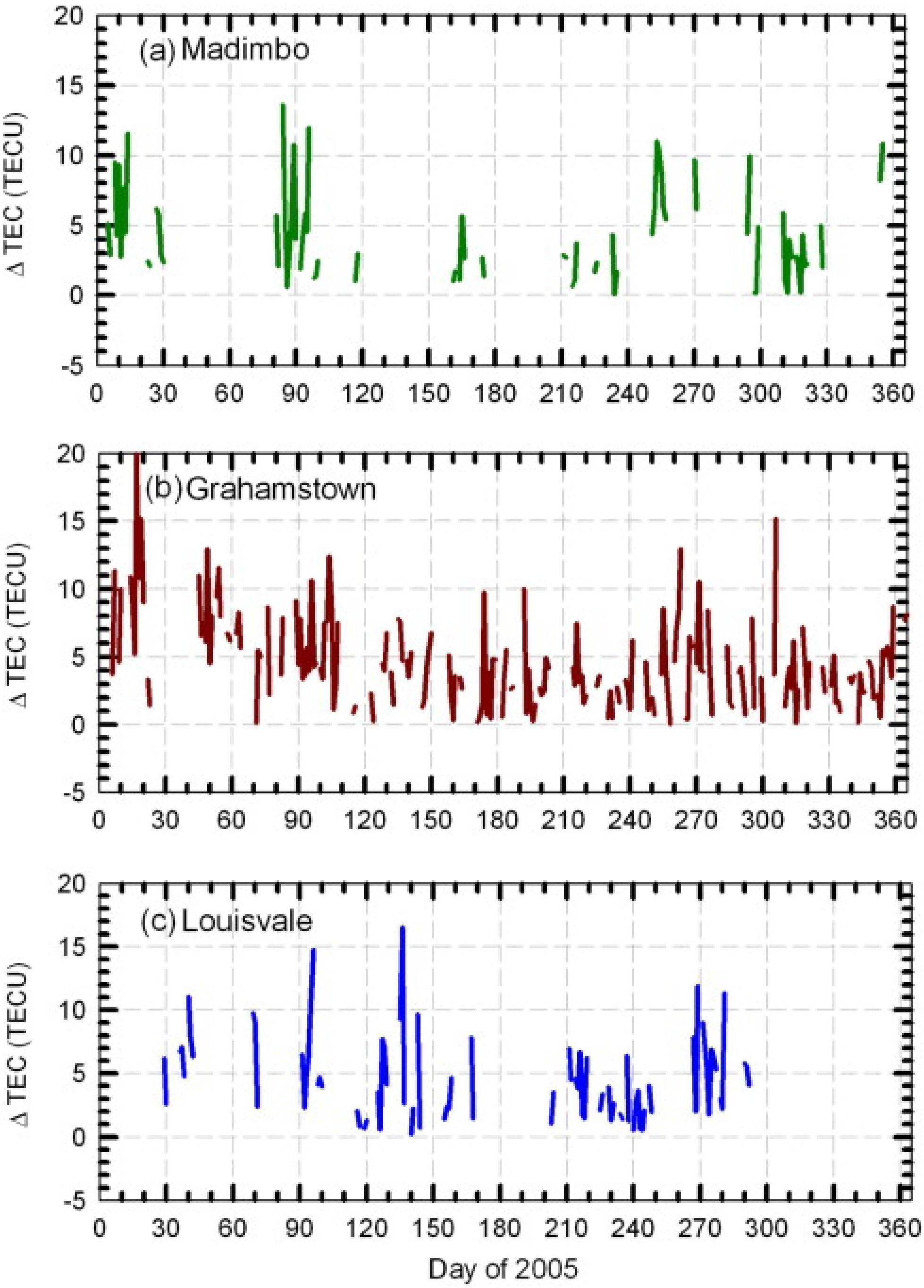

Fig. 6. Similar to Fig. 5, but is shown for the period 2005 near solar minimum conditions.

4.4. Variations of equivalent midday ionospheric total slab thickness parameters

The slab thickness may be regarded as the depth of an imaginary ionosphere, which has the measured TEC and uniform electron density equal to the maximum electron density of the actual ionosphere ([Breed and Goodwin, 1997] and [Belehaki et al., 2003a]). For a given foF2 value, the slab thickness depends on the electron density versus height profile, the sharper the peak electron density the smaller is the slab thickness. The slab thickness is calculated using both GTEC and ITEC parameters according to the formulas:

$$\tau_t = \frac{\mathrm{GTEC}}{\mathrm{NmF2}} = \alpha \cdot \frac{\mathrm{GTEC}}{\mathrm{foF2}^2}, \tag{3}$$

and

$$\tau_i = \frac{\mathrm{ITEC}}{\mathrm{NmF2}} = \alpha \cdot \frac{\mathrm{ITEC}}{\mathrm{foF2}^2}. \tag{4}$$

For τ in km, TEC in TECU, and foF2 in MHz, α equals 806 according to the relation between the electron density NmF2 and the critical frequency foF2:

$$\mathrm{NmF2}/1\ \mathrm{m}^{-3} = \frac{1}{80.6}\left(\frac{\mathrm{foF2}}{1\ \mathrm{Hz}}\right)^2, \tag{5}$$

The τ_t includes the electron content of both the ionosphere and the plasmasphere up to ∼20,200 km while τ_i provides electron contents of the bottomside and topside ionosphere up to ∼1000 km (Breed and Goodwin, 1997; Belehaki et al., 2003a).

Fig. 7(a)–(c) depicts the midday variation of slab thickness parameters τ_t and τ_i over (a) Madimbo, (b) Grahamston, and (c) Louisvale for the year 2002 near solar maximum conditions. It is inferred from the panels that variation trends of τ_t and τ_i are in good agreement over all stations and show pronounced seasonal variation with maximum values (∼200 km to ∼500 km) around summer and minimum values (∼200 km to ∼300 km) around winter. These results are consistent with Miro et al. (1999) results obtained over El Arenosillo (37.1°N, 6.7°W) middle latitude station. However, this seasonal trend is in phase with near midday plasma temperature ([Miro et al., 1999] and [Belehaki et al., 2003a]). A noticeable difference between τ_t and τ_i is also evident in all panels which is attributed to the plasmaspheric electron content contributions in determining the total slab thickness particularly towards the year 2002 (high solar activity). It is important to mention that under a quiet-day time the ionosphere is mainly controlled by diffusion (e.g., Förster and Jakowski, 2000).

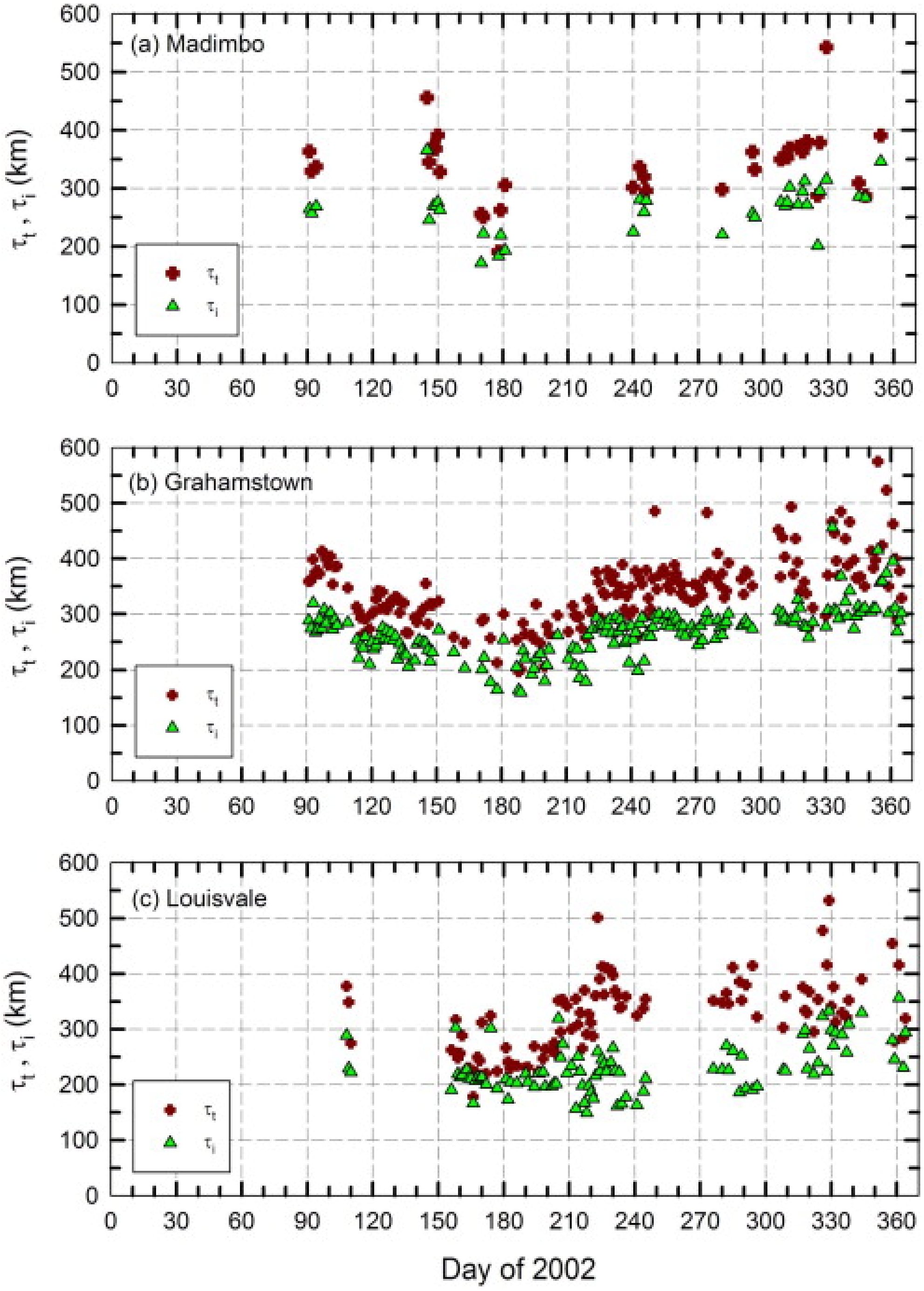

Fig. 7. Variation of the midday ionospheric slab thickness parameters τ_j (red cross) and τ_i (green triangles) over (a) Madimbo, (b) Grahamstown, and (c) Louisvale for the year 2002 near solar maximum conditions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 8(a)–(c) is similar to Fig. 7, but shown for the year 2005 near solar minimum conditions. The variation trends of τ_t and τ_i over all stations are in good agreement and show a less pronounced seasonal variation which maximizes (∼200 km to ∼500 km) around summer and minimizes around winter (∼150 km to ∼300 km). Of interest is the small difference between of τ_t and τ_i over all stations compared to the year 2002 of high solar activity. This could be indicating a state close to diffusion equilibrium between the ionosphere and the plasmasphere (Miro et al., 1999).

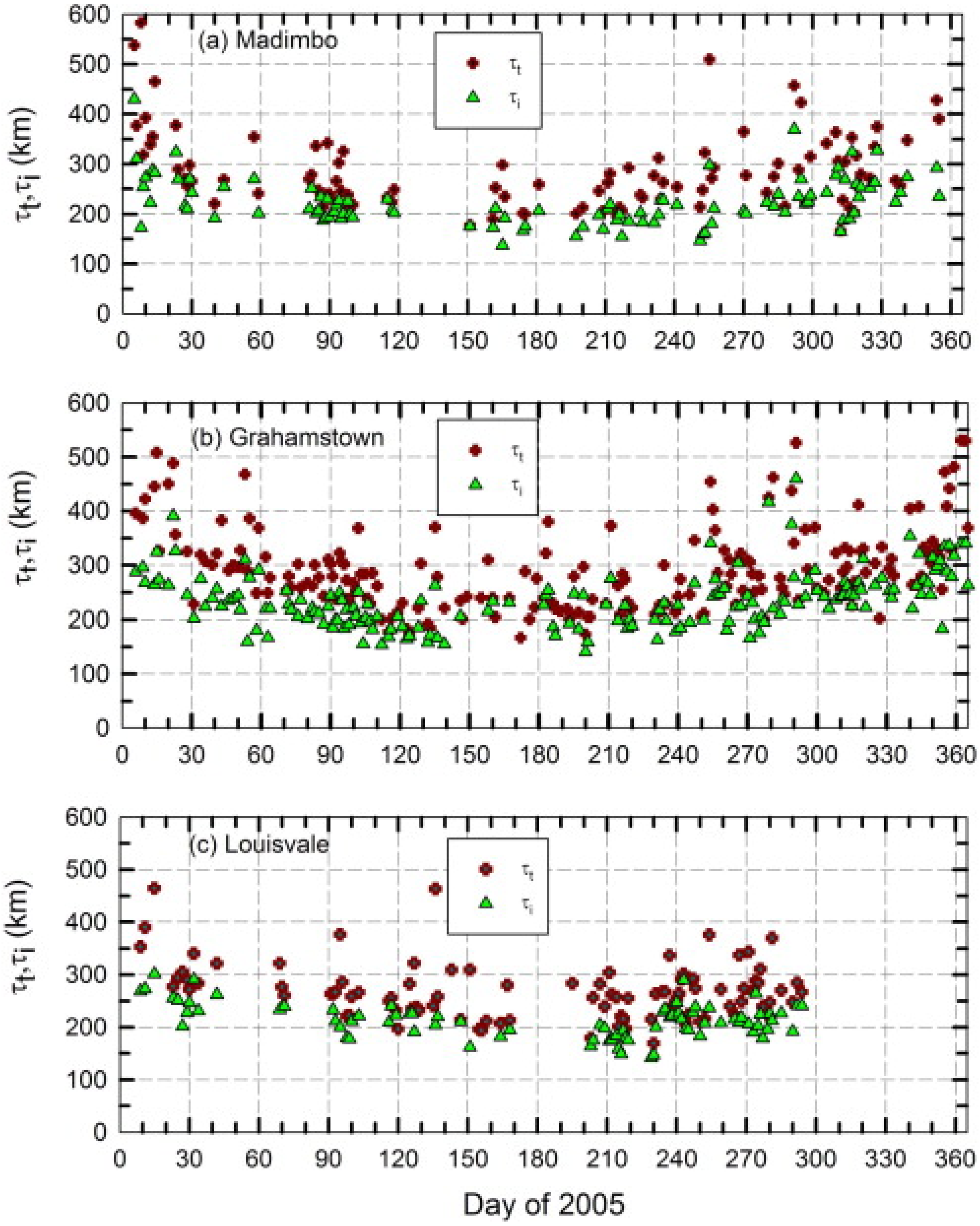

Fig. 8. Similar to Fig. 7, but shown for period 2005 near solar minimum conditions.

By comparison, it is evident that the midday ionospheric and total slab thickness parameters τ_t and τ_i computed over all stations for year 2002 and year 2005, maximizes around summer season and minimizes around winter. This is in contrast with the midday GTEC and ITEC, which maximizes around the equinoxes as discussed in Sections Sections 4.1 and 4.2, respectively. These results are consistent with Bhonsle et al. (1965) findings of mid-latitude seasonal variation of slab thickness and TEC derived from beacon satellite measurements.

5. Summary and conclusions

This work reports on the validation of UNB-IMT midday GTEC results using the ionosonde-derived total electron content (ITEC) measurements over South Africa during the years 2002 and 2005 corresponding to solar maximum and minimum conditions, respectively. It was found that in general the two techniques showed a good degree of agreement. In particular, the variation trends of GTEC and ITEC over all stations showed a pronounced seasonal variation for the period near solar maximum, with maximum values (~80 TECU) around autumn and spring equinoxes, and minimum values (~22 TECU) around winter and summer. For the period near solar minimum, the seasonal variation trends were found to be less pronounced with maximum values (~30 TECU) around equinoxes and minimum (~10 TECU) values around summer and winter.

A comparison between GTEC and ITEC values found that in general a good inter-technique correlation exists during solar maximum and minimum periods. Finally, the residual $\Delta TEC = GTEC - ITEC$ was computed for the ionosonde locations. It was evident that ΔTEC, which likely correspond to plasmaspheric electron content, showed a pronounced seasonal variation with maximum values (~20 TECU) around equinoxes and minimum (~5 TECU) around winter near solar maximum. For the period 2005, plasmaspheric electron content was found to be highly variable with a minimum value of ~2 TECU and a maximum value of ~10 TECU over all stations. The variation trend of plasmaspheric electron content near solar minimum was found to display a complicated picture. This could be due to reported inaccuracies in calculation of ITEC parameters towards solar minimum. In particular, inaccuracies associated with the application of topside extrapolation method with constant scale height in calculation of ITEC parameters (Reinisch et al., 2007). Further studies are needed in future to investigate the latter.

The ionospheric and total slab thickness parameters were also computed. It was evident that these parameters over all stations, maximize around summer season, which is in contrast with the seasonal variation of GTEC and ITEC, which maximizes around equinoxes. These results are consistent with early studies of TEC using beacon satellite (Bhonsle et al., 1965) and, therefore, verified the use of UNB-IMT as one of the tools for future ionospheric TEC research and application over South Africa.

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