Evaluating the IRI topside model for the South African region: An overview of the modelling techniques

P. Sibanda and L.A. McKinnell*

* Department of Physics and Electronics, Rhodes University, Grahamstown, South Africa

Abstract

The representation of the topside ionosphere (the region above the F2 peak) is critical because of the limited experimental data available. Over the years, a wide range of models have been developed in an effort to represent the behaviour and the shape of the electron density (*Ne*) profile of the topside ionosphere. Various studies have been centred around calculating the vertical scale height (VSH) and have included (a) obtaining VSH from Global Positioning System (GPS) derived total electron content (TEC), (b) calculating the VSH from ground-based ionosonde measurements, (c) using topside sounder vertical *Ne* profiles to obtain the VSH. One or a combination of the topside profilers (Chapman function, exponential function, sech-squared (Epstein) function, and/or parabolic function) is then used to reconstruct the topside *Ne* profile. The different approaches and the modelling techniques are discussed with a view to identifying the most adequate approach to apply to the South African region's topside modelling efforts. The IRI-2001 topside model is evaluated based on how well it reproduces measured topside profiles over the South African region. This study is a first step in the process of developing a South African topside ionosphere model.

1. Introduction

The ionosphere, the ionised component of Earth's upper atmosphere, is a complex medium that varies significantly with time and space. The complexity of the ionosphere is due to mechanisms inherent in the Sun–Earth system. (The radiation from the sun and Earth's atmosphere form a system which is driven by the transfer of energy from the solar radiation to the constituent particles of Earth's atmosphere.) Other factors such as season, position in the solar cycle, and geomagnetic activity also significantly affect the behaviour of the ionosphere.

The topside ionosphere extends from the F2 peak to the upper transition height (UTH). In the topside ionosphere, plasma distributions are controlled by the plasma transport processes, and field-aligned plasma flows play an important role in determining the plasma density profiles (Venkatraman, 1999). The UTH is the transition height between O^+ and H^+ dominated plasma regions (Marinov et al., 2004). Traditionally for South Africa, ionosondes which measure the bottomside and give a modelled topside are used to determine day to day and hour to hour variations in the ionosphere. The South African Bottomside Ionospheric Model (SABIM) was developed using the data from the three South African ionosondes and is able to give a representation of how the ionosphere varies over the South African region given the geographical location, time of day and season, solar activity, and geomagnetic activity (McKinnell, 2002). This model is only valid up to the height of the F2 peak, hmF2. There is a need to expand this model to include the topside ionosphere above the F2 peak. While many researchers ([Bilitza et al., 2006], [Huang and Reinisch, 2001], [Reinisch and Huang, 2001], [Radicella and Zhang, 1995], [Stankov et al., 2002], [Kutiev et al., 2006], [Pulinets et al., 2002] and [Depuev and Pulinets, 2004]) around the world have studied the topside ionosphere and the International Reference Ionosphere (IRI) predicts the global topside, none, that the authors know of, has concentrated on the South African topside. Bilitza et al. (2006) presented a comprehensive review of the different approaches to topside modelling and their implication for the IRI model. They described the major modelling efforts focusing on the specific goal of improving the representation of the electron density profiles in the IRI model. In earlier studies, Bilitza (2004) evaluated the IRI topside model, and a comparison of the model results with Alouette and ISIS topside sounder data showed a systematic overestimation.

This study focuses on the South African region with the specific goal of developing a topside model for this region that will be smoothly fitted to the current South African bottomside model with the emphasis on the correct representation of the shape of the electron density (*Ne*) profile in the topside. As a first step towards achieving this objective, this paper presents an overview of the current status of topside modelling and the techniques used in the various available topside models. An evaluation of the IRI model under different conditions is presented in order to determine how the IRI represents the topside over the South African region. The IRI topside model *Ne* profiles are compared with the measured profiles from the ISIS 2 topside sounder. This study hopes to contribute to and compliment the work other groups are doing in other regions.

2. Approaches to topside modelling

The general approach to topside modelling involves two major aspects that make it difficult and complex, (1) calculating the vertical scale height (VSH), and (2) finding and choosing the right profile functions and defining other important profile shape factors.

2.1. Vertical scale height (VSH)

The vertical scale height (VSH) is a key parameter of every topside model. Various literature describe different techniques developed for calculating the vertical scale height (Stankov et al., 2002). These methods include:

1. Calculating VSH from GPS derived TEC (Jakowski et al., 2002) and (Stankov et al., 2003). The resulting VSH is then used to reconstruct the *Ne* profiles up to satellite height.

2. Obtaining the Chapman VSH from ground-based ionosonde measurements (Huang and Reinisch, 2001). In this method, an estimate of the topside scale height is derived from the shape of the bottomside profile at the F2 peak. Recently an improvement of this earlier approach has been developed (Reinisch et al., 2007). In the improved approach, the scale height varies slowly with altitude around the F2 peak and then increases rapidly at the UTH.

3. Calculating the VSH from topside sounder data. Depuev and Pulinets (2004) used data from the Intercosmos 19 satellite. Their approach showed the importance of the longitudinal variation of the scale height for global modelling. Kutiev et al. (2006) used both the ISIS 2 and the Intercosmos 19 topside sounder data to extract the vertical O^+ scale height which is defined as the lowest gradient of the measured *Ne* profiles.

2.2. Basic topside *Ne* profile functions

Because of its complicated nature, a number of approaches to modelling the topside ionosphere have been developed over the years. Mathematical functions commonly used to describe the altitude profile of the electron density in the topside ionosphere include the following:

Chapman function given as

$$N(h)=N(h_m)(e^{c[1-z-e^{-z}]}) \qquad (1)$$

where $z = \frac{h-h_m}{2H}$ and c specifies a distinct formulation of this function depending on assumptions related to the electron recombination theory (Stankov et al., 2003) such that; it is an α-Chapman function when $c = 0.5$ and β-Chapman function when $c = 1$.

Sech-squared (Epstein) function given by

$$N(h) = N(h_m)\,\mathrm{sech}^2\left(\frac{h-h_m}{2H}\right) \tag{2}$$

Exponential function

$$N(h) = N(h_m)\exp\left(-\frac{h-h_m}{H}\right) \tag{3}$$

Parabolic function

$$N(h) = N(h_m)\left(1-\left[\frac{h-h_m}{2H}\right]^2\right) \tag{4}$$

In each case, h_m is the peak density height and H is the scale height, a key parameter in determining the shape of the ionospheric *Ne* profiles in these functions. Note that the Chapman scale height in (1) is the neutral scale height. Fig. 1 presents a comparison between vertical electron density profiles obtained with the different mathematical functions above for a given scale height of 100 km.

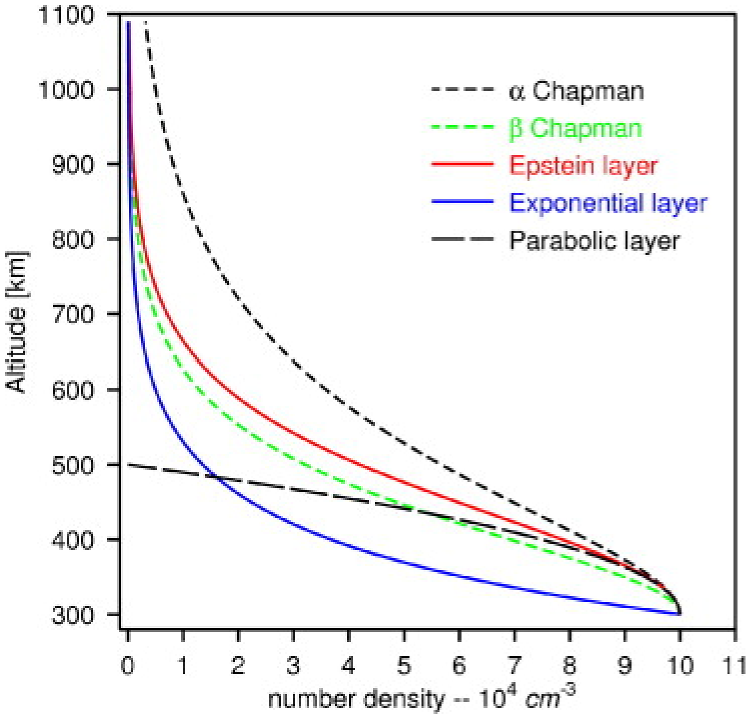

Fig. 1. The shape of the topside electron density profile computed with different profilers (Stankov et al., 2003).

3. Topside ionosphere models

In recent years, a wide range of models have been developed to represent and describe the topside ionospheric behaviour and variation. Topside modelling efforts include mainly empirical models (models based on measurements) and analytical models (models based on orthogonal function fits to the output obtained from numerical models). Also there has been a growing interest in developing models based on real-time measurements (such as GPS-based methods) using data assimilation techniques. This relatively new approach presents the potential for greatly improving modelling efforts.

3.1. The topside in the IRI model

The IRI model is the most comprehensive and widely used ionospheric empirical model (Schunk and Sojka, 1992) and provides information on the global distribution of the electron density amongst other parameters. The formulation of altitude variation of the electron density in the topside is based on the Booker function (Coisson et al., 2006) to represent the exponential scale heights which are computed with the Bent et al.

(1972) model. A specific scale height is defined for each of the three altitude segments into which the topside is divided (Bilitza et al., 2006) and (Bilitza, 2004). It was built on Alouette and ISIS topside sounder data and it has been improved and updated over the years (Bilitza et al., 2006). The IRI-2001 model is compared with measured data from the ISIS 2 topside sounder database to determine how the model represents the topside in the region over Southern Africa.

3.1.1. Comparison between measured and IRI model profiles

Electron density profiles from the ISIS 2 topside sounder were used for comparison with the IRI-2001 model to test how they represent the topside ionosphere in our region. The data were received on CD from the National Space Science Data Centre (NSSDC). A total of 908 profiles exist for the Southern African region from this database. It was difficult to find more than one electron density profile for a particular location and time sector, since only sets of sparse points along the satellite path exist. This is generally the nature of satellite measurements. Data for 1973 were used for the model comparison because it is one of the few years that contained profiles covering most parts of the year with each season represented. Sample profiles representing the different seasons were chosen from the database and the corresponding IRI-2001 model profiles where generated. The IRI-2001 model was updated with the measured peak parameters, foF2 and hmF2 from the measured topside profiles in an attempt to anchor the predicted profile and concentrate on the profile shape. Due to the difficulties in the scaling of the topside sounder ionograms caused by the inversion technique (Bilitza, 2004), in some cases, the profiles do not reach all the way down to the peak. To solve this problem, an α-Chapman function was fitted to the lower end of the profile using a non-linear least squares approach to find the best peak parameters (hmF2 and foF2) and the scale height. Fig. 2 shows an example profile with a Chapman function fitted to the lower end. This procedure was done to all the profiles used. In most cases, the calculated peak parameters were very close to the values given in the data.

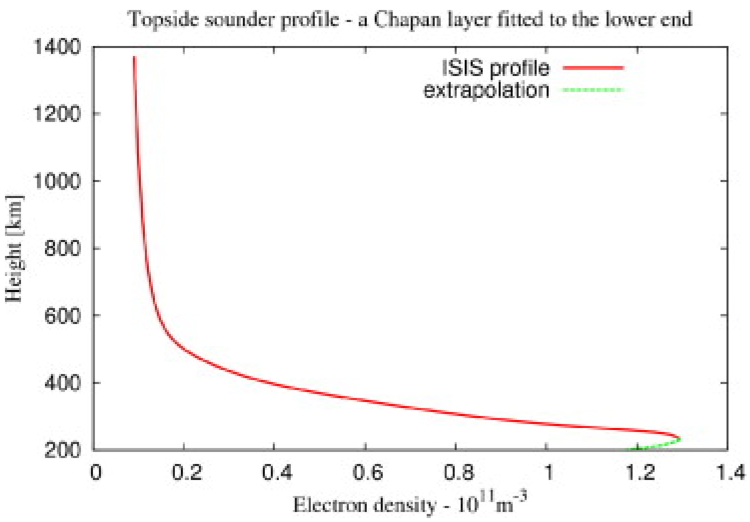

Fig. 2. ISIS 2 topside electron density profile with an α-Chapman function fitted to the lower part of the profile.

Sample topside sounding data from satellite orbits over the South African region during the daytime were used for comparison with the model results. This sample data occurred on 16 March 1973, 07 June 1973, 16 September 1973, and 07 December 1973 providing profiles which all fell at about the same latitude of around 25.0–26.9°S. The data sample was chosen such that the four different seasons were each represented by a day, and individual profiles from those days corresponding to the daytime sector (08:00 to 14:00 UT) were selected. The profiles used each occurred at a different hour due to the difficulty in obtaining satellite data from the same hour covering all seasons. The ratio between the topside sounder *Ne* and IRI-2001 *Ne* was computed for each profile pair and the results are shown in Fig. 3.

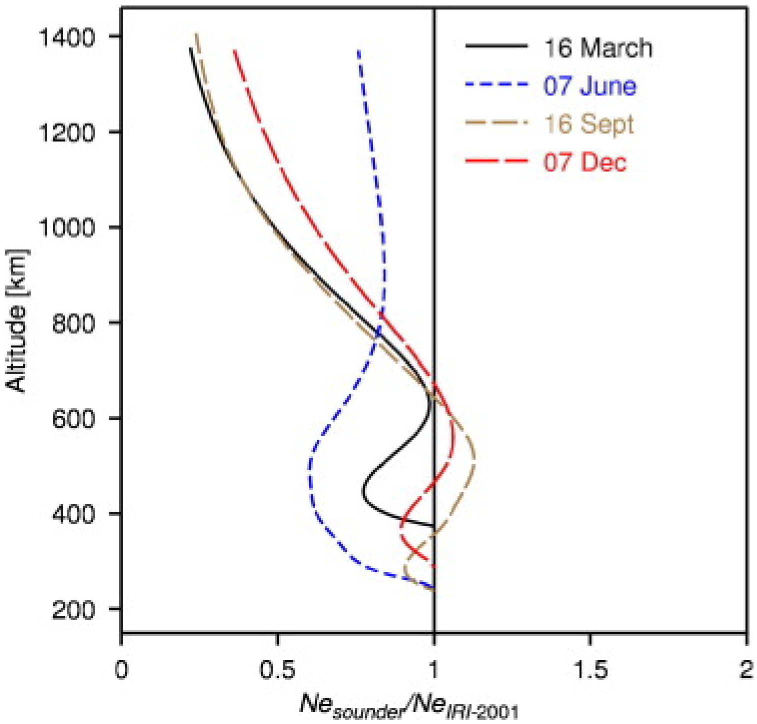

Fig. 3. The ratio between the topside sounder data from the ISIS 2 and the IRI-2001 model for the sample moments on 16 March, 07 June, 16 September, and 07 December 1973. The local times for the profiles range from 08:00 to 14:00, with each profile at its own hour within that range.

On the basis of these results, we concluded that the IRI-2001 model slightly overestimates the *Ne* at higher altitudes (above about 800 km) as indicated by the values of the calculated ratios which are much less than 1 as compared to the lower altitudes. Fig. 4 shows plots for each of the four sample topside sounder profiles considered and shows how each individual profile pair compares. The model is more representative of the measured data at the lower altitudes, below about 800 km, with greater variation at higher altitudes, except for the profile on 07 June 1973 where the IRI generated profile is consistently larger in *Ne* than the measured profile through out.

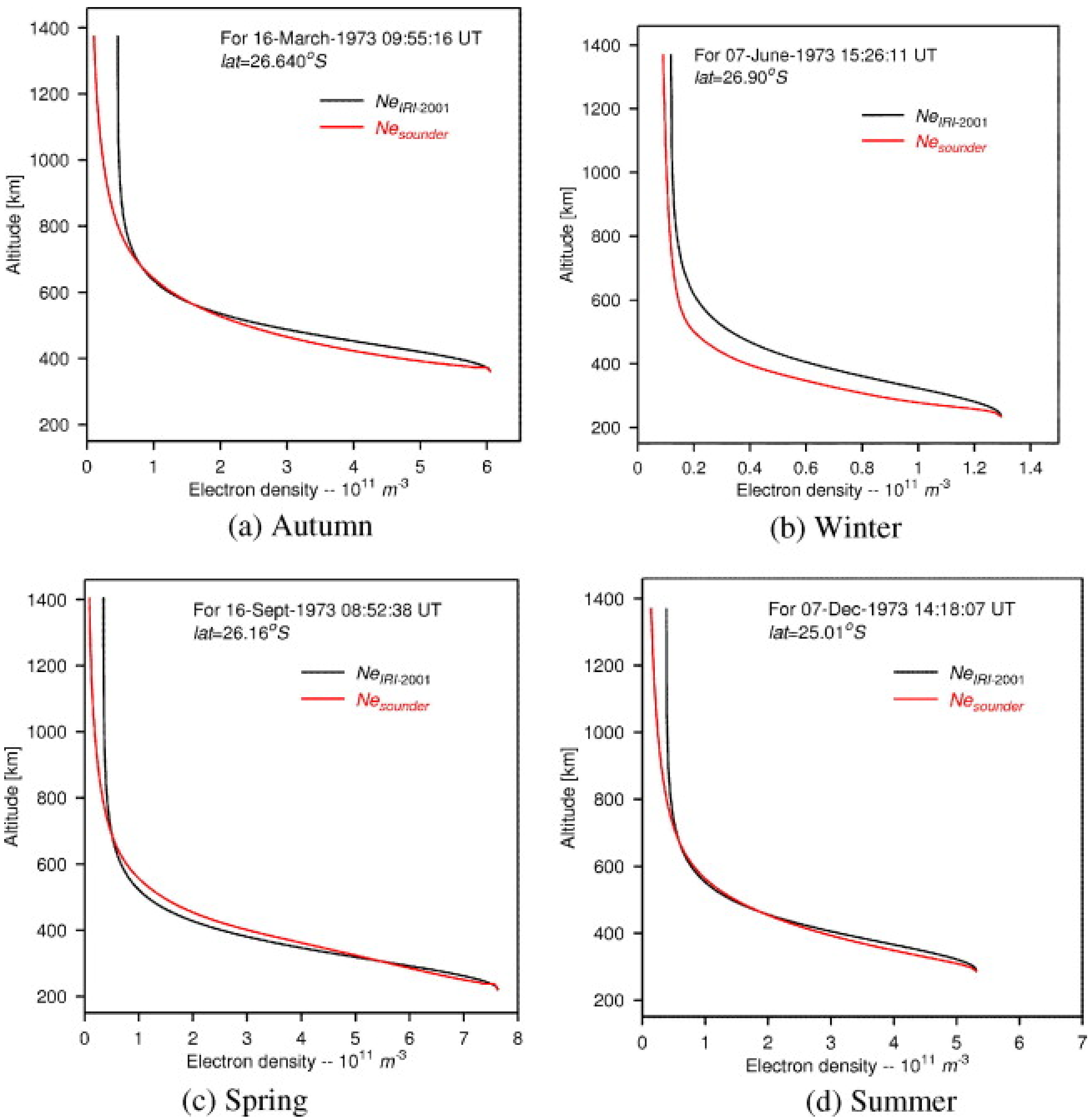

Fig. 4. Sample ISIS 2 electron density profiles compared with the corresponding IRI-2001 model profiles for the dates sampled.

In order to quantify the deviation of the model from the measured profile, we make use of the concept of residual standard deviation. The residual standard deviation is a goodness of fit measure; that is, the smaller the residual standard deviation, the closer the model data is to the measured data. The residual standard deviation was calculated for each profile pair using the following equation:

$$RSD = \sqrt{\Sigma(Ne_{sounder} - Ne_{IRI})^2/(N - k)} \quad (5)$$

where N is the number of data sample points for each profile and k is the number of model parameters. In this case, k represents the number of effective parameters that were varied for each profile. These included geographic latitude and longitude, year, day of year, hour (UT), and the peak parameters hmF2 and foF2. This procedure was undertaken in order to be able to test the performance of the model as a function of location and time of day. Fig. 5 shows the variation of the *RSD* over the South African region during the different seasons in 1973 indicating how the IRI-2001 model reproduces measured data.

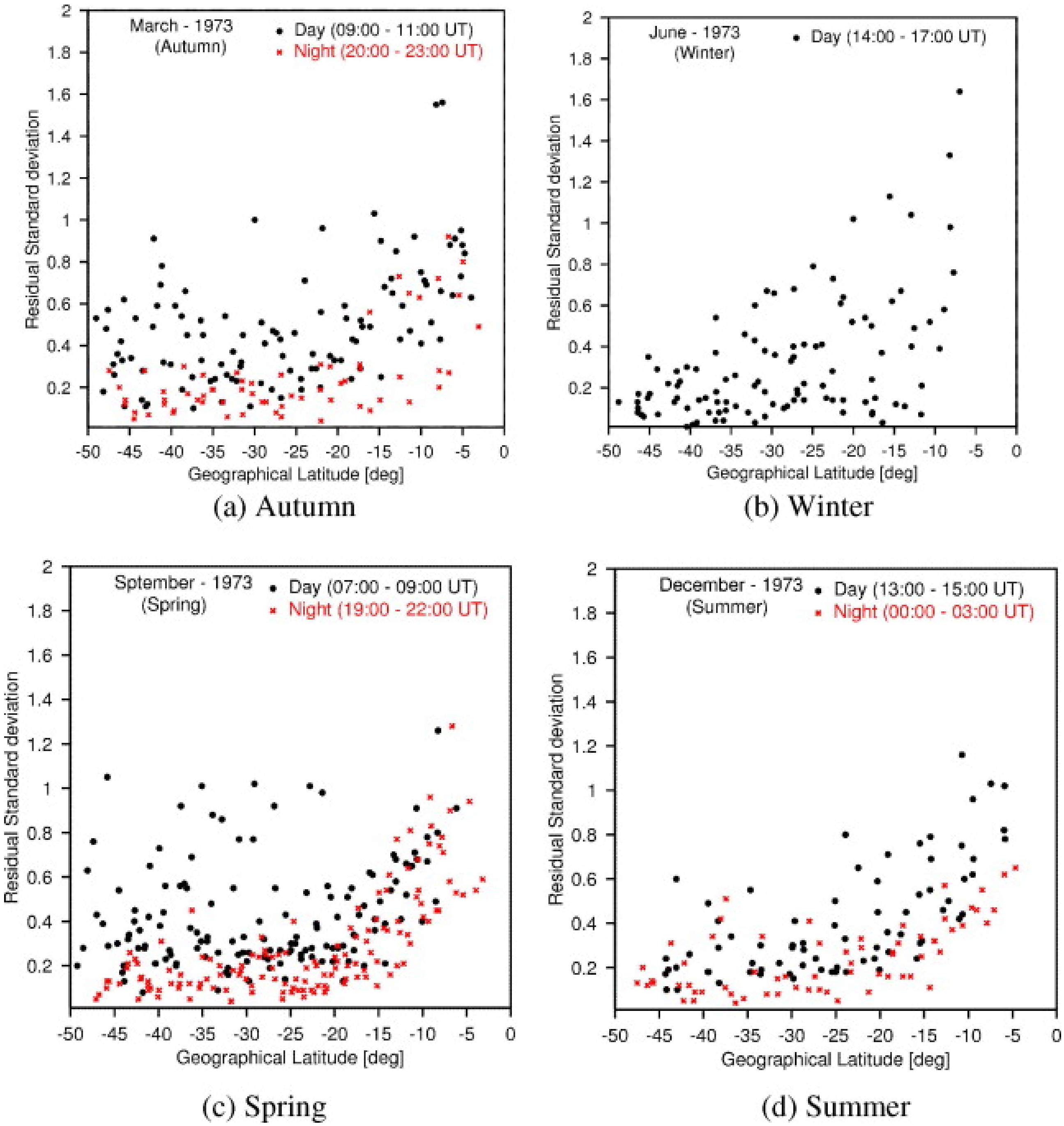

Fig. 5. The residual standard deviation computed for the different seasons to show how the IRI-2001 model fits to the measured data over a range of Southern African latitudes and during different time sectors, nighttime and daytime. There were no profiles for the nighttime sector in winter.

From the figure, the *RSD* is generally higher during the daytime than during the nighttime for all the different seasons. This indicates that the model has improved performance during nighttime compared to daytime. The *RSD* at latitudes ranging from 20°S to 50°S is generally lower than at lower latitudes (<20°S) which shows that the model is better at reproducing the measured data at the higher latitudes than it is at the lower latitudes.

3.1.2. Representation of the topside in ionosondes

The vertical electron density profile up to the peak of the F2 layer is directly calculated using the information provided by the ionogram. A method was developed by Huang and Reinisch (2001) and Reinisch and Huang (2001) to approximate and reconstruct the profile above the F2 peak using an α-Chapman function with a scale height derived from the bottomside profile shape around the F2 peak. The complete electron density profile in ionosonde measurements consists of a measured bottomside and a modelled topside part. This makes it possible to calculate TEC from ionosonde measurements up to about 1000 km altitude.

3.2. Other topside modelling efforts

A wide range of topside models have been developed in recent years. A detailed review of the various approaches to topside modelling with the emphasis on their implications for the IRI was presented by Bilitza (2004). In a related study, Schunk and Sojka (1992) presented a general overview of approaches to ionospheric modelling which include empirical models, analytical models, theoretical models and models involving data assimilating techniques. Cander et al. (1998) reviewed the progress in ionospheric modelling and described the various types of modelling approaches with a view to assessing their applicability to space weather forecasting. This study follows on these reviews with a specific focus on the implications of the various modelling techniques for the topside modelling efforts in South Africa. The sections that follow highlight some of the topside modelling efforts with particular emphasis on the techniques applied. In general, the techniques involve a unique method of calculating the scale height and use standard profile functions which include the Chapman function, the Epstein function, the exponential function, and the parabolic function to reconstruct the electron density profile. The scale height is the key parameter in determining the shape of the electron density profile.

3.2.1. F2 topside and IMAGE/RPI plasmaspheric model

Reinisch et al. (2007) present a new model which is a merge of the ionosonde topside model with the IMAGE/RPI plasmaspheric model that use a varying α-Chapman function (vary-Chap) that takes into account scale height variation with altitude. (Reinisch and Huang, 2001) and (Huang and Reinisch, 2001) and Reinisch et al. (2004) successfully showed how to reconstruct the topside electron density profile assuming an α-Chapman profile with a constant scale height deduced from ground-based ionosonde measurements. The new approach is an improvement on this earlier approach and makes it possible to merge the F2 topside model with the IMAGE/RPI plasmaspheric model (Reinisch, 2004). In the new approach, the scale height is allowed to vary slowly with altitude around the F2 peak and then increases rapidly at the UTH. The model uses the plasmasphere density profile data measured with the RPI instrument on the IMAGE satellite and topside sounder data from the ISIS 2 satellite (Reinisch et al., 2007).

3.2.2. The NeQuick model

Radicella and Zhang (1995) developed the NeQuick model applying the DGR "profiler" concept introduced by Di Giovani and Radicella (1990) which uses an Epstein function with varying scale height given by Eq. (6) (Radicella and Leitinger, 2001).

$$H(h) = \frac{kB_{bot}}{n}\left\{\frac{1+12.5(h-h_m)}{100kB_{bot}+0.125[h-h_m]}\right\} \tag{6}$$

The model is based on ionosonde data and topside sounder data from the ISIS and Intercosmos 19 satellites. It assumes a close correlation between topside and bottomside thickness parameters (Bilitza et al., 2006); thus, the scale height (Eq. (6) above) is given as a function of the bottomside thickness B_{bot}, and k is a correction factor that depends on the F peak density.

3.2.3. Parameterised empirical model (Intercosmos 19)

Pulinets et al. (2002) developed a high solar activity model based on Intercosmos 19 topside sounder data for the global topside electron density distribution. They use an Epstein function with a varying scale height described by

$$H=H_0+k(h-h_m) \tag{7}$$

Depuev and Pulinets (2004) applied the same technique based on a larger database of topside sounder profiles from Intercosmos 19 satellite to develop a global empirical model of the topside electron density. They subdivided the model coefficients by the longitudinal sectors and showed the importance of the longitudinal variation of the scale height for the global modelling.

3.2.4. Topside model based on GPS TEC measurements

Stankov et al. (2002) have developed a method to reconstruct the vertical electron density distribution in the topside ionosphere and plasmasphere using GPS-based TEC measurements, ionosonde measurements, and O^+–H^+ measurements. The technique involves construction of a system of equations based on the different topside profiler functions; Chapman, Epstein, and exponential. The system of equations include a representation of the principle of plasma quasi-neutrality at the F2 peak height, a representation of the fact that the densities of the hydrogen and oxygen ions are equal at the UTH (Stankov and Muhtarov, 2001) and the fact that the topside TEC is the difference between the GPS TEC and the bottomside ionosonde TEC. The solution of such a system of equations provides the unknown topside ion scale heights which are then used to reconstruct a unique electron density profile for a given location and time of measurement (Stankov et al., 2003).

3.2.5. Topside Sounder Model (TSM)

Kutiev et al. (2006) describes a Topside Sounder Model (TSM) to calculate topside scale height based on topside sounder *Ne* profiles from the Intercosmos 19 and ISIS satellites. The model provides the VSH as a function of month of the year, local time, geomagnetic latitude, solar flux $F_{10.7}$ and K_p index. They use a technique that describes the vertical plasma scale height by a multi-variable polynomial constructed from Chebyshev and trigonometric base-functions, which are fitted to the data in the five-dimensional space. From each individual *Ne* profile, they extract the vertical O^+ scale height (VSH) defined as the lowest gradient of the measured *Ne* profiles and the O^+–H^+ transition height (TH) defined as the height, at which the upward extrapolated O^+ density becomes half the measured *Ne*. They have proposed a Topside Sounder Model Profiler (TSMP) which provides electron density profiles for three different analytical shapes: sech-squared, α-Chapman, and exponential that incorporates the TSM and uses the model quantities as anchor points to reconstruct the topside electron density profile.

4. Summary

The ISIS 2 database was used to test the ability of the IRI-2001 model to reproduce measured data over the Southern African latitudes. To give a prediction that better represents the topside profile in the South African region, the IRI-2001 model requires updating with the measured peak characteristics, foF2 and hmF2. The residual standard deviation concept was used to evaluate the deviation of the modelled profiles from the measured profiles. This illustrated an improved performance of the model in the latitudes range from (20°S to 50°S) than in the lower latitudes (below 20°S). The *RSD* values were generally lower during the nighttime than during the daytime indicating a better match between the IRI-2001 predicted values and measured data during the nighttime. The *RSD* was computed for each sample profile pair considered.

Various groups are making significant progress with regard to topside modelling and our understanding of the topside ionospheric dynamics. A number of modelling efforts and the techniques applied have been identified and described. This will aid our efforts of identifying a method to best represent the distribution of the electron density in the topside ionosphere for the South African region. Currently, the greatest problem facing the various groups trying to model the topside is the lack of sufficient topside data. The scarcity of topside measurements and the difficulty involved in making such measurements emphasises the need for accurate topside models.

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References

Bent, R.B., Llewellyn, S.K., Schmid, P.E. Description and evaluation of the Bent ionospheric model, in: Space and Missile Syst. Org, Rep. SAMSO TR-72-81, vols. 1–3, Natl. Tech. Inf. Serv., Springfield Va., 1972.

Bilitza, D. A correction for the IRI topside electron density model based on Alouette/ISIS topside sounder data. Adv. Space Res. 33, 838–843, 2004.

Bilitza, D., Reinisch, B.W., Radicella, S.M., Pulinets, S., Gulyaeva, T., Triskova, L. Improvements of the International Reference Ionosphere model for the topside electron density profile. Radio Sci. 41 (RS5S15), 1–8, 2006.

Cander, L.R., Leitinger, R., Levy, M.F. Ionospheric models including the auroral environment, in: Proceedings of the ESA Workshop on Space Weather, ESA WPP-155, ESTEC, Noordwijk, pp. 135–141, 1998.

Coisson, P., Radicella, S.M., Leitinger, R., Nava, B. Topside electron density in IRI and NeQuick: features and limitations. Adv. Space Res. 37 (5), 937–942, 2006.

Depuev, V.H., Pulinets, S.A. A global empirical model of the ionospheric topside electron density. Adv. Space Res. 34 (9), 2016–2020, 2004.

DiGiovani, G., Radicella, S.M. An analytical model of the electron density profile in the ionosphere. Adv. Space Res. 10 (11), 27–30, 1990.

Huang, X.Q., Reinisch, B.W. Vertical electron content from ionograms in real time. Radio Sci. 36 (2), 335–342, 2001.

Jakowski, N., Kutiev, I.S., Heise, S., Wehrenpfennig, A. A topside ionosphere/plasmasphere model for operational applications, in: Proceedings of the XXVII URSI General Assembly, Maastricht. Available from: www.ursi.org/Proceedings/ProcGA02/papers/ p2174.pdf, pp. 2174–2177, 2002.

Kutiev, I.S., Marinov, P.G., Watanabe, S. Model of topside ionosphere scale height based on topside sounder data. Adv. Space Res. 37 (5), 943–950, 2006.

Marinov, P., Kutiev, I., Watanabe, S. Empirical model of O+–H+ transition height based on topside sounder data. Adv. Space Res. 34 (9), 2015–2022, 2004.

McKinnell, L.A. A neural network based ionospheric model for the bottomside electron density profile over Grahamstown, South Africa, Ph.D. thesis. Rhodes University, Grahamstown, South Africa, 2002.

Pulinets, S., Depuev, V., Karpachev, A., Radicella, S., Danilkin, N. Recent advances in topside profile modeling. Adv. Space Res. 29 (6), 815–823, 2002.

Radicella, S.M., Leitinger, R. The evolution of the DGR approach to model the electron density profiles. Adv. Space Res. 27 (1), 35–40, 2001.

Radicella, S.M., Zhang, M.L. The improved DGR analytical model of the electron density height profile and total electron content in the ionosphere. Ann. Geophys. 38 (1), 35–41, 1995.

Reinisch, B.W. Tenth international digisonde training seminar at UMass Lowell reviews state of real time mapping of the ionosphere. IEEE Antennas Propag. Mag. 45 (5), 110–117, 2004.

Reinisch, B.W., Huang, X.Q. Deducing topside profiles and total electron content from bottomside ionograms. Adv. Space Res. 27 (1), 23–30, 2001.

Reinisch, B.W., Huang, X.Q., Belehaki, A., Shi, J.K., Zhang, M.L., Ilma, R. Modeling the IRI topside profile using scale heights from ground-based ionosonde measurements. Adv. Space Res. 34 (9), 2026–2031, 2004.

Reinisch, B.W., Nsumei, P., Huang, X., Bilitza, D.K. Modelling the F2 topside and plasmasphere for IRI using IMAGE/RPI and ISIS data. Adv. Space Res. 39 (5), 731–738, 2007.

Schunk, R.W., Sojka, J.J. Approaches to ionospheric modelling, simulation and prediction. Adv. Space Res. 12 (6), 317–326, 1992.

Stankov, M.S., Muhtarov, P.Y. Reconstruction of the electron density profile from the total electron content using upper transition level and vertical incidence sounding measurements. C. R. Acad. Bulg. Sci. 54 (9), 45–48, 2001.

Stankov, S.M., Warnant, R., Jodogne, J.C. Operational model for realtime reconstruction of the electron density profile using GPS TEC measurements, in: Proceedings of the XXVII URSI General Assembly, Maastricht. Available from: www.ursi.org/Proceedings/ProcGA02/ papers/p1571.pdf, pp. 1571–1574, 2002.

Stankov, S.M., Jakowski, N., Heise, S., Muhtarov, P., Kutiev, I., Warnant, R. A new method for reconstruction of the vertical electron density distribution in the upper ionosphere and plasmasphere. J. Geophys. Res. 108 (A5), 1164, doi:10.1029/2002JA009570, 2003.

Venkatraman, S. Nighttime behaviour of the equatorial topside ionosphere, Ph.D. thesis, University of Texas at Dallas, William B. Hanson Centre for Space Sciences. Richardson, TX 75080, 1999.