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NeQuick 2 and IRI Plas VTEC predictions for low latitude and South American sector

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Abstract

Using vertical total electron content (VTEC) measurements obtained from GPS satellite signals the capability of the NeQuick 2 and IRI Plas models to predict VTEC over the low latitude and South American sector is analyzed. In the present work both models were used to calculate VTEC up to the height of GPS satellites. Also, comparisons between the performance of IRI Plas and IRI 2007 have been done. The data correspond to June solstice and September equinox 1999 (high solar activity) and they were obtained at nine stations. The considered latitude range extends from 18.4°N to −64.7°N and the longitude ranges from 281.3°E to 295.9°E in the South American sector. The greatest discrepancies among model predictions and the measured VTEC are obtained at low latitudes stations placed in the equatorial anomaly region. Underestimations as strong as 40 TECU [1 TECU = 10^{16} m^{-2}] can be observed at BOGT station for September equinox, when NeQuick2 model is used. The obtained results also show that: (a) for June solstice, in general the performance of IRI Plas for low latitude stations is better than that of NeQuick2 and, vice versa, for highest latitudes the performance of NeQuick2 is better than that of IRI Plas. For the stations TUCU and SANT both models have good performance; (b) for September equinox the performances of the models do not follow a clearly defined pattern as in the other season. However, it can be seen that for the region placed between the Northern peak and the valley of the equatorial anomaly, in general, the performance of IRI Plas is better than that of NeQuick2 for hours of maximum ionization. From TUCU to the South, the best TEC predictions are given by NeQuick2.

The source of the observed deviations of the models has been explored in terms of CCIR foF2 determination in the available ionosonde stations in the region. Discrepancies can be also related to an unrealistic shape of the vertical electron density profile and or an erroneous prediction of the plasmaspheric contribution to the vertical total electron content. Moreover, the results of this study could be suggesting that in the case of NeQuick, the underestimation trend could be due to the lack of a proper plasmaspheric model in its topside representation. In contrast, the plasmaspheric model included in IRI, leads to clear overestimations of GPS derived TEC.

Keywords: NeQuick 2 model; IRI Plas model; Vertical total electron content

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1. Introduction

The ionosphere is the part of the Earth's upper atmosphere where ions and electrons are present in quantities sufficient to affect the propagation of radio waves (Rishbeth and Garriot, 1969).

The ionosphere of middle latitudes has been the most explored and is the best understood. There, the ionization is produced almost entirely by energetic ultraviolet and X-ray emissions from the Sun, and is removed again by chemical recombination processes that may involve the neutral atmosphere as well as the ionized species. The movement of ions, and the balance between production and loss, are affected by winds in the neutral air (Hunsucker and Hargreaves, 2003).

The above mentioned processes are also present at low latitudes, but in that region additional physical processes take place and generate the equatorial ionization anomaly (EIA). The EIA is characterized by a trough in the ionization concentration at the equator and crests at about 15° in magnetic latitude (Appleton, 1946) in each hemisphere and has been described as arising from the electrodynamics at the equator. Since an electric field (**E**) is established perpendicular to the magnetic field (**B**), the plasma over the equator is lifted to higher altitudes with a drift velocity given by:

$$v = E \wedge B/B^2 \quad (1)$$

Then it diffuses along the magnetic field lines under the gravitational and pressure gradient forces. As a consequence, the plasma is redistributed forming two ionization crests on both sides of the equator.

Above the ionosphere is the plasmasphere, a torus of corotating plasma, surrounding the Earth out to 3–7 times its radius. Above 1000 km height neutral atmosphere densities are so small that they have little effect on the charged particles motion, governed by electric and magnetic fields (Davies, 1990). The positive ions are predominantly protons and the plasmasphere is practically synonymous of the protonosphere. In addition, some ionic diffusive processes take place from the ionosphere to the plasmasphere on nighttime when the plasma densities decrease.

The presence of the charged particles in the ionosphere brings about the possibility of radio communication over large distances by making use of one or more ionospheric reflections.

For radio communication, it is essential to predict the behaviour of the ionosphere region that will affect a given radio communication circuit. Such a prediction will identify the time periods, the regions and the sections of high frequency bands that will allow or disrupt the use of the selected high frequency communication circuit. This need for prediction leads to modeling the ionosphere.

Moreover, the ionosphere produces several effects on transionospheric radio waves. Most of these effects are proportional to the number of free electrons in a cylinder of unit cross section extending from the ground to the top of the ionosphere, (total electron content, TEC). TEC is an important magnitude of the ionosphere and plays a vital role in the performance of the satellite-based communication and navigation systems. The highest vertical TEC (VTEC) values in the world occur at the crests of the EIA.

The ionospheric corrections to be applied to accurately determine the satellite position are proportional to the TEC along the radar-to-satellite path (Hartman and Leitinger, 1984). Thus, for ionospheric corrections, TEC estimations from ionospheric models represent a useful tool.

Several physical, empirical and semiempirical models (e.g. Anderson,1973; Llewellyn and Bent, 1973; Chiu, 1975; Bent et al.,1976; Anderson et al.,1987; Bilitza,1990; Ezquer et al.,1992,1994; Scidá et al., 2016 among others) have been developed to predict the behaviour of ionospheric magnitudes. Empirical models are wide spread tools to describe ionospheric conditions. Nowadays these models are used, not only for the long term predictions, but for the real time description of ionospheric conditions, as the IRTAM model (Reinisch et al., 2014)

One of the most widely used empirical models is the International Reference Ionosphere (IRI) (Rawer et al., 1978; Bilitza, 1990, 2001; Bilitza and Reinisch, 2008; Bilitza et al., 2014). A working group of about 50 international ionospheric experts is in charge of developing and improving the IRI model. Over time as new data became available and new modeling techniques emerged, steadily improved editions of the IRI model have been published (Bilitza et al., 2014). The model's capability for predicting the ionospheric behaviour is continuously checked by the scientific community (Ezquer et al., 1994; Mosert et al., 2004; Buresova et al., 2006; Migoya Orué et al., 2008; Bilitza, 2009; McKinnell and Oyeyemi, 2009; Ezquer et al., 2014; among many others).

Several authors compared the IRI VTEC predictions with GPS VTEC measurements (Mosert et al., 2007; Bhuyan and Borah, 2007; Scidá et al., 2009; Chauhan and Singh, 2010; Aggarwal, 2011; Bhuyan and Hazarika, 2013; Akala et al., 2013; Asmare et al., 2014; Tariku, 2015; Leong et al., 2015; Okoh et al., 2015; Kumar, 2016; among others) However, these comparisons have a limitation because the GPS VTEC is a measure of electron content from the ground to the height of the GPS satellites (20,200 km), while the IRI model only calculates the TEC up to 2000 km. The plasmaspheric electron content between 2000 km and 20,200 km is not considered by the model.

Taking into account that:

TEC_{IRI} = ionospheric electron content (electron content up to 2000 km of height).
TEC_{GPS} = ionospheric electron content + plasmaspheric electron content (electron content up to 20,200 km of height),

when a comparison of both TEC is done the possible results are:

(a) $TEC_{IRI} > TEC_{GPS}$. This result indicates that the model overestimates the ionospheric electron density.
(b) $TEC_{IRI} = TEC_{GPS}$. Also this result indicates that the model overestimates the ionospheric electron density or that the plasmaspheric contribution is not relevant.
(c) $TEC_{IRI} < TEC_{GPS}$. This would be an expected result but it is not possible to know if the model gives a good prediction of the ionospheric electron density because it is compared with a measurement made up to the height of satellites.

The IRI extended to Plasmasphere (IRI Plas) (Gulyaeva et al., 2002), has been proposed as one of the possible candidate models for the plasmasphere extension of the IRI model (Gulyaeva and Bilitza, 2012). With IRI Plas is possible to calculate VTEC up to the height of the GPS satellites. The plasmasphere extension of IRI, IRI-Plas, is based on the Russian Standard Model of the Ionosphere (SMI), an empirical model derived from many years of measurements designed to represent typical conditions as a function of geomagnetic and solar activity (Chasovitin et al., 1998). It presents global vertical analytical profiles of electron density smoothly fitted to IRI electron density profiles at an altitude of topside half peak density (400–600 km) and extended towards the plasmapause (up to 36,000 km).

Recently, the performance of IRI Plas has been assessed by some researchers. For example, Zakharenkova et al. (2015) found that this model does not represent correctly the VTEC variations over European mid latitudes and mainly overestimates GPS VTEC especially for low and moderate solar activity. Maltseva et al. (2015) compared the performance of IRI Plas and the Neustrelitz Global Model (NGM) in predicting VTEC in different geographical areas. They found that in middle and high latitude areas, $VTEC_{NGM}$ and $TEC_{IRI\ Plas}$ provide better results than $VTEC_{IRI}$. Moreover their results show that IRI Plas model is better than NGM except for winter months. In low latitudes areas, the NGM model has shown advantages.

The NeQuick is another globally recognized empirical model. The NeQuick 2 (Nava et al., 2008) is the last released version of the family of the Trieste–Graz ionospheric 'profilers' (Di Giovanni and Radicella, 1990; Hochegger et al., 2000; Radicella and Leitinger, 2001). NeQuick was specifically designed to calculate the electron concentration as a function of geographic position, height, solar activity and time for trans-ionospheric applications. In this model, as in the case of IRI, the F2 region peak values are calculated using the ITU-R coefficients (former CCIR coefficients) (International Radio Consultative Committee CCIR 1967a,b). The model is able also to compute the TEC along vertical and slant ground-to-satellite ray paths by numerical integration. NeQuick 2 model has been adopted by the International Telecommunication Union, Radiocommunication Sector (ITU-R) Recommendation P. 531-9 as a suitable method for TEC modeling (Radicella, 2009 and references therein).

It is noteworthy that NeQuick2 model has the advantage of calculating the total electron content up to the height of the GPS satellites. The topside of NeQuick is a simplified approximation to a diffusive equilibrium, with an increase with height of the electron density scale height used.

The performance of NeQuick has been assessed by several workers. For example, Coïsson et al. (2004), compared VTEC and slant TEC (STEC) computed with different empirical models, among them, IRI and NeQuick, using Global Ionospheric Maps (GIM) data from CODE and STEC obtained from some North American and European GPS stations. They noted that NeQuick was the model with a more stable behaviour in terms of space and time with respect to IRI and Klobuchar (1987) models. Bidaine and Warnant, 2010 made a comparison with NeQuick (first and second model versions) adapted to ionosonde parameters and TEC data from three European mid-latitude GPS stations. They conclude that the second version of NeQuick presents evident improvements and highlighted the importance of the new topside formulation. Mahrous et al., 2014 compared VTEC values obtained with NeQuick 2 and GNSS derived TEC data from two Egyptian stations (HELW and ALEX2) during different months of years 2010–2013. The model showed a better representation of VTEC values during the year of low solar activity (2011) especially during daytime hours.

Some comparison studies about the assessment of the performance of IRI and NeQuick in different regions have been published. For example, Leong et al., 2015 analyzed how TEC from these models are correlated with GPS TEC from a Malaysian station during the ascending phase of 24th solar cycle. They found a high correlation among both models and GPS values particularly on solstice. The greatest disagreements have been found during post sunset hours and in equinox. Similar results have been reported by Venkatesh et al., 2014, who analyzed the period 2010–2013 with GPS derived and IRI, NeQuick modeled VTEC under a meridian on the Brazilian region.

In order to extend VTEC studies to other latitudes, but focusing in the complex region around the EIA, in the present work we compare the NeQuick 2 and IRI Plas models predictions with the GPS-derived VTEC data obtained at nine stations in the west South American sector during 1999, a year of high solar activity. It has to be noted that in Scidá et al. (2012) a comparative study with the same configuration of GPS stations has been done with IRI 2007 model. The cases of underestimations of the model obtained have been attributed to the contribution of the plasmasphere, so in the present work we attempt to analyze that hypothesis.

2. Data and results

The location of the considered GPS stations is given in Table 1 and Fig. 1.

Table 1
GPS receiver stations listed from North to South.

Stations	Latitude	Longitude	Geomag. Lat.	Geomag. Lon.	DIP
PUR3 (Puerto Rico)	18.4	292.9	24.8	3.0	46.44
MARA (Maracaibo)	10.7	288.3	22.1	358.9	38.43
BOGT (Bogotá)	4.6	285.9	16.5	355.5	30.20
RIOP (Riobamba)	−1.6	281.3	9.7	351.0	20.16
AREQ (Arequipa)	−16.4	288.5	−5.0	358.4	−7.14
TUCU (Tucumán)	−26.8	294.7	−15.5	4.1	−25.38
SANT (Santiago)	−33.1	289.3	−21.7	359.2	−33.01
RIOG (Río Grande)	−53.8	292.2	−42.4	1.6	−51.13
PALM (Palmer)	−64.7	295.9	−53.3	4.1	−58.55

The data correspond to June 1999 (Rz12: 93.0) and September 1999 (Rz12: 102.0). The observed monthly mean Ap index values were around 7 and 18 for the months of June and September 1999, respectively. The month of September presented a couple of moderate geomagnetic events with Dst of −60 and −91 nT. However, in the present work we consider monthly median values of VTEC with a twofold objective, first because the empirical models used here are designed to represent median and quiet conditions of the ionosphere, and also because it has the advantage of being less affected by large deviations in the ionospheric characteristics that can occur during magnetic storms.

Hourly time interval resolution was considered for the diurnal variation.

The “La Plata Ionospheric Model” (LPIM) was used to obtain VTEC from single GPS station observations. Briefly, VTEC is calculated using the so-called geometry – free linear combination of both L1 and L2 GPS carrier phase observations:

$$\phi_1 - \phi_2 = \alpha\mathrm{STEC} + \tau_r + \tau^s + \upsilon \tag{2}$$

where ϕ_1 and ϕ_2 are the observations, STEC is the slant total electron content along line of sight, τ_r and τ^s are the L1-L2 inter-frequency electronic delays produced in the hardware of the receiver and the satellite (expressed in linear units), α is a constant to convert linearly in TEC units and υ is the L_1-L_2 combined measurement error.

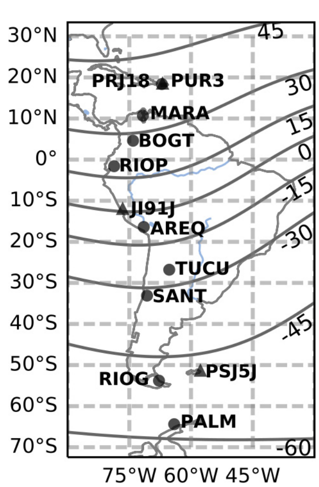

Fig. 1. Map of GPS (circles) and ionosonde (triangles) stations used in the study. Lines of Modip are also indicated.

The thin layer ionosphere approximation was used in connection with the mapping function that relates STEC and VTEC at the ionospheric penetration point (IPP):

$$\frac{VTEC_{IPP}}{STEC} \cong \cos z_{IPP} = \sqrt{1 - \left(\frac{R}{R+H}\right)^2 \cos^2(z)} \tag{3}$$

where R is the mean Earth’s radius, H (350 km in this work) is the height of the thin layer above the Earth’s surface and z and z_{IPP} are the satellite zenith distance at the observation point and at the IPP respectively.

Further, the spatial and temporal variability of the $VTEC_{IPP}$ is represented by means of a bi-linear expansion on the IPP coordinates with time dependent coefficients:

$$VTEC_{IPP} = a_{00}(t) + a_{10}(t)(\lambda_{IPP} - \lambda)\cos(\varphi) + a_{01}(t)(\mu_{IPP} - \mu) \tag{4}$$

where t is the Universal Time, λ and φ are the geographic longitude and latitude of the IPP and the receiver, and μ the corresponding modip latitude (Rawer, 1984). The time-dependent coefficients were represented with the step-wise function $a_{i,j}(t) = a_{i,j,k}$, $a_{i,j,k}$ being a constant for the interval $[t_k, t_k + \Delta t)$ and Δt (5min in this work) being the refreshing interval.

A set of $3 \times 1440/\Delta t$ (864 in this work) $a_{i,j,k}$ parameters per day were estimated applying the Least Square method to the observations collected by each GPS receiver. Simultaneously, the inter-frequency electronic delays of the satellites and the receiver where also estimated and used, in connection with Eqs. (2) and (3) to compute $VTEC_{IPP}$ from the observed data:

$$VTEC_{IPP} = \frac{\cos z_{IPP}}{\alpha}[\phi_1 - \phi_2 - \tau_r - \tau^s] \tag{5}$$

Lastly, the $VTEC_{IPP}$ with $Z_{IPP} \leq 25°$ values were retained, and from this subset of data hourly mean VTEC values were computed for each station. The angular aperture of the cone around the zenith of the station was set at 25° to optimize the representation of the VTEC at the station site ($VTEC_{IPP}$ values near the zenith and better operation of the mapping function). The price paid for that was to have fewer observations. The latter is the cause of the bumps that appear for some hours and in some sites.

The sampling interval of observation was 30 s. A more detailed explanation of the model is described by Brunini et al. (2001).

The modeled values presented here were obtained using the web pages: www.ionolab.org, for the IRI Plas predictions and https://t-ict4d.ictp.it/nequick2/nequick-2-web-model for the NeQuick ones. Both models have been run up to the height of GPS satellites, R12 as solar activity index and with CCIR option for foF2 and M3000 parameters.

The relative deviation between model predictions and VTEC measurements was calculated as:

$$D\% = [(\text{Model prediction} - \text{measured value})/\text{measured value}] \times 100 \qquad (6)$$

The results for PUR3, June, are shown in Fig. 2 (top panel). The VTEC is in TECU ($10^{16}\ m^{-2}$). It can be seen that both models show a similar daily variation to that observed in the measurements but, NeQuick2 underestimates the electron content for all hours of the day. The greatest relative deviation is observed at 0 LT (−43%). At hours of maximum ionization (14 LT) the NeQuick2 underestimation reaches a value close to 14 TECU. Regarding to IRI Plas a very good agreement is observed

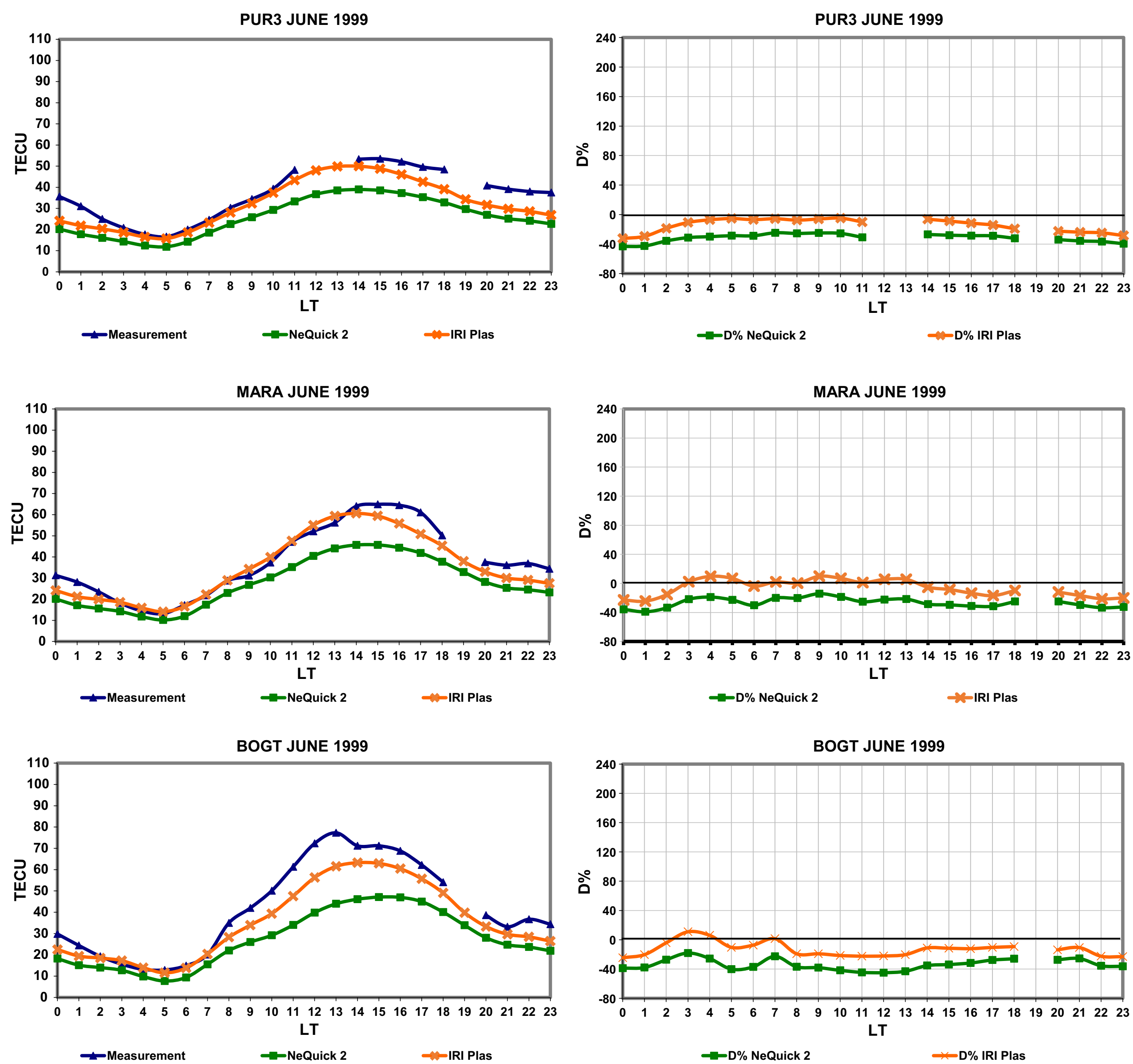

Fig. 2. Modeled and experimental VTEC and D%. Low latitude, stations PUR3, MARA and BOGT. June 1999 (Rz12: 93).

from last hours of the night to the maximum VTEC value and few cases show deviations greater than 20%.

Similar results are observed for MARA in the middle panel of Fig. 2. There, it can be seen that for 16 LT the NeQuick2 prediction is 20 TECU lower than the obtained measurement and that the underestimation of the other model is close to 9 TECU. For BOGT, both models underestimate VTEC for almost all hours of the day as can be seen in the bottom panel of Fig. 2. At time of maximum ionization the deviation reaches −40% and −20% for NeQuick2 and IRI Plas predictions, respectively. NeQuick2 underestimates the VTEC in 33 TECU at 13 LT and IRI Plas give good predictions for the hours around of the minimum VTEC.

Fig. 3, June solstice, shows the models behaviours for the southern low latitude stations. We can notice that, in general, both models underestimate VTEC over RIOP and AREQ for maximum ionization hours. Moreover, for RIOP it can be seen that the daily variation given by both models is different to that observed in the measurements. The rate of increasing ionization after sunrise given by the models is lower than that observed in measurements and the maxima electron content values are predicted for later hours than those observed in the GPS VTEC values. The relative deviation for hours of maxima ionization obtained with NeQuick2 reaches values greater than 40% (almost 50%) for NeQuick2 and 30–35% for IRI Plas. In the panel for AREQ we can observe a good agreement

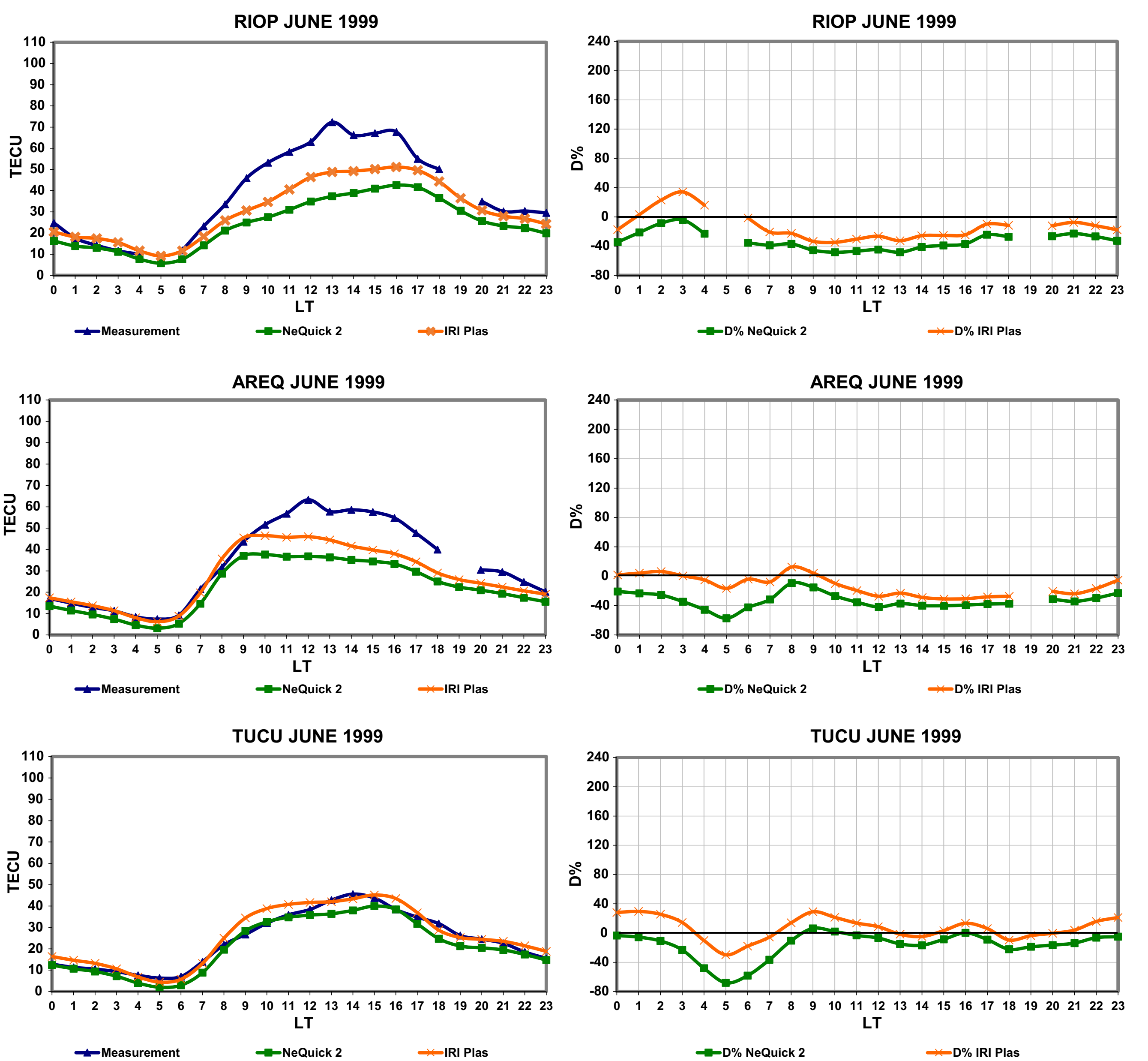

Fig. 3. Modeled and experimental VTEC and D%. Low latitude, stations RIOP, AREQ and TUCU. June 1999 (Rz12: 93).

between IRI Plas predictions and measurements from 0 to 9 LT while NeQuick2 underestimates VTEC in few TECU (close to 4 TECU). For hours of maximum VTEC the underestimations obtained with the considered models are close to 30% and 40%.

The best predictions are given for TUCU station. The absolute value of D% (|D%|) obtained with both models is lower than 20% for most hours of the day.

From Figs. 2 and 3 we can see that in the Northern Hemisphere the highest VTEC measurements were observed at BOGT, placed near the Northern peak of the EIA, while they were observed at Arequipa instead of Tucumán, in the Southern Hemisphere. These results suggest that the Southern peak of the EIA moved equator ward during this period.

In top panel of Fig. 4, June solstice, the results for the station SANT are displayed. In general, good predictions are observed. In most of the cases the deviations between models predictions and measured values are equal or lower than 4 TECU. The high values of D% observed in some cases are produced by the low values of measured VTEC. For RIOG station, we can see that NeQuick2 underestimates VTEC in about 1–3 TECU from 0 to 6 LT. Moreover, overestimations for hours of maximum ionization and good predictions for 7, 8, 20, 21, 22, 23 LT are obtained with this model. On the other hand, IRI Plas gives

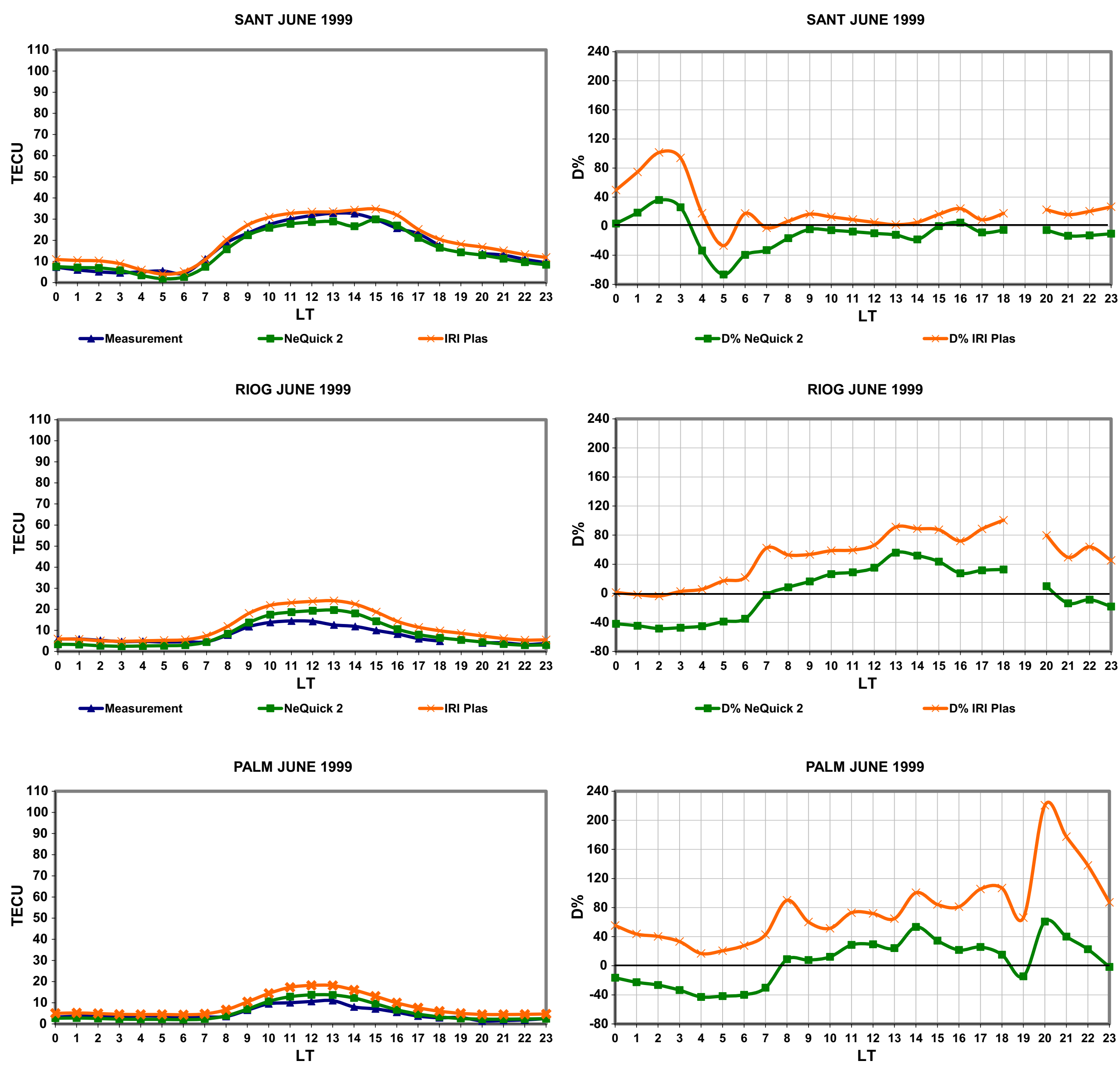

Fig. 4. Modeled and experimental VTEC and D%. Middle and high latitude, stations SANT, RIOG and PALM. June 1999 (Rz12: 93).

good prediction from 0 to 6 LT and overestimates VTEC for the rest of the day reaching a difference of more than 10 TECU in hours of maximum ionization. The VTEC values obtained with IRI Plas are greater than those obtained with the other model. In the case of PALM the results are similar to those of RIOG.

In Figs. 5–7 the results for the September equinox are displayed. The top panel of Fig. 5 shows good NeQuick2 predictions for hours close to maximum VTEC over PUR3. The relative deviation obtained with this model from 8 LT to 23 LT, in general, is lower than 10%. For this station, it can be seen an overestimation obtained with IRI Plas for daylight hours with D% close to 40% for 10 LT. The results for MARA, displayed in the middle panel of Fig. 5, show that NeQuick 2 underestimates the electron content for most hours of the day and gives good predictions after 20 LT, while IRI Plas overestimates VTEC for several hours of the day.

Strong underestimations obtained with NeQuick2 are observed from 12 to 21 LT for BOGT (see bottom panel of Fig. 5) where D% reached -40%. For 15 LT, NeQuick2 prediction is 44 TECU lower than the measurement. In general, good NeQuick2 predictions are obtained for the rest of the day. Regarding to IRI Plas, it can be seen that this model also underestimates VTEC over BOGT for hours of maximum ionization but, its predictions are closer

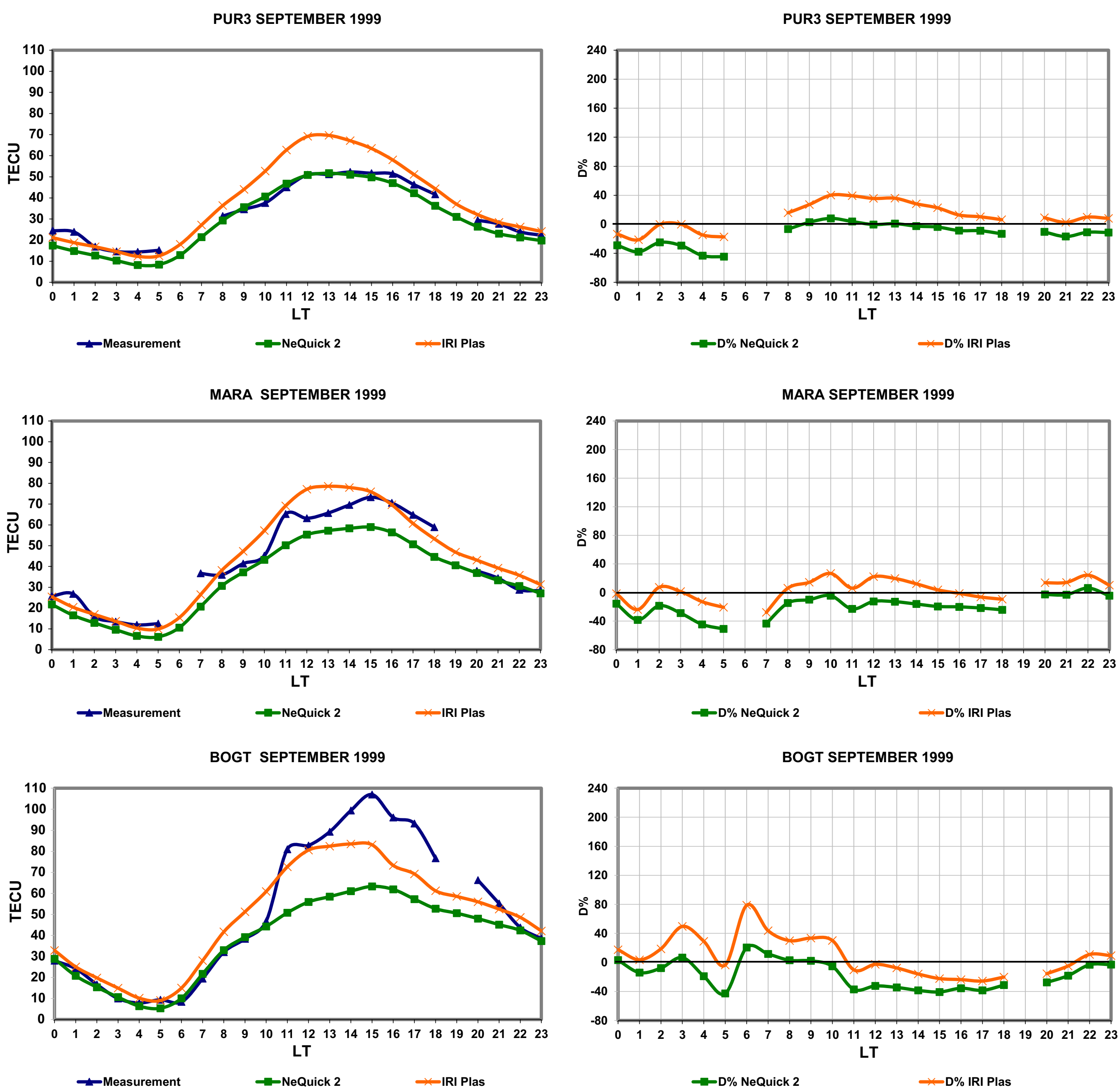

Fig. 5. Modeled and experimental VTEC and D%. Low latitude, stations PUR3, MARA and BOGT. September 1999 (Rz12: 102).

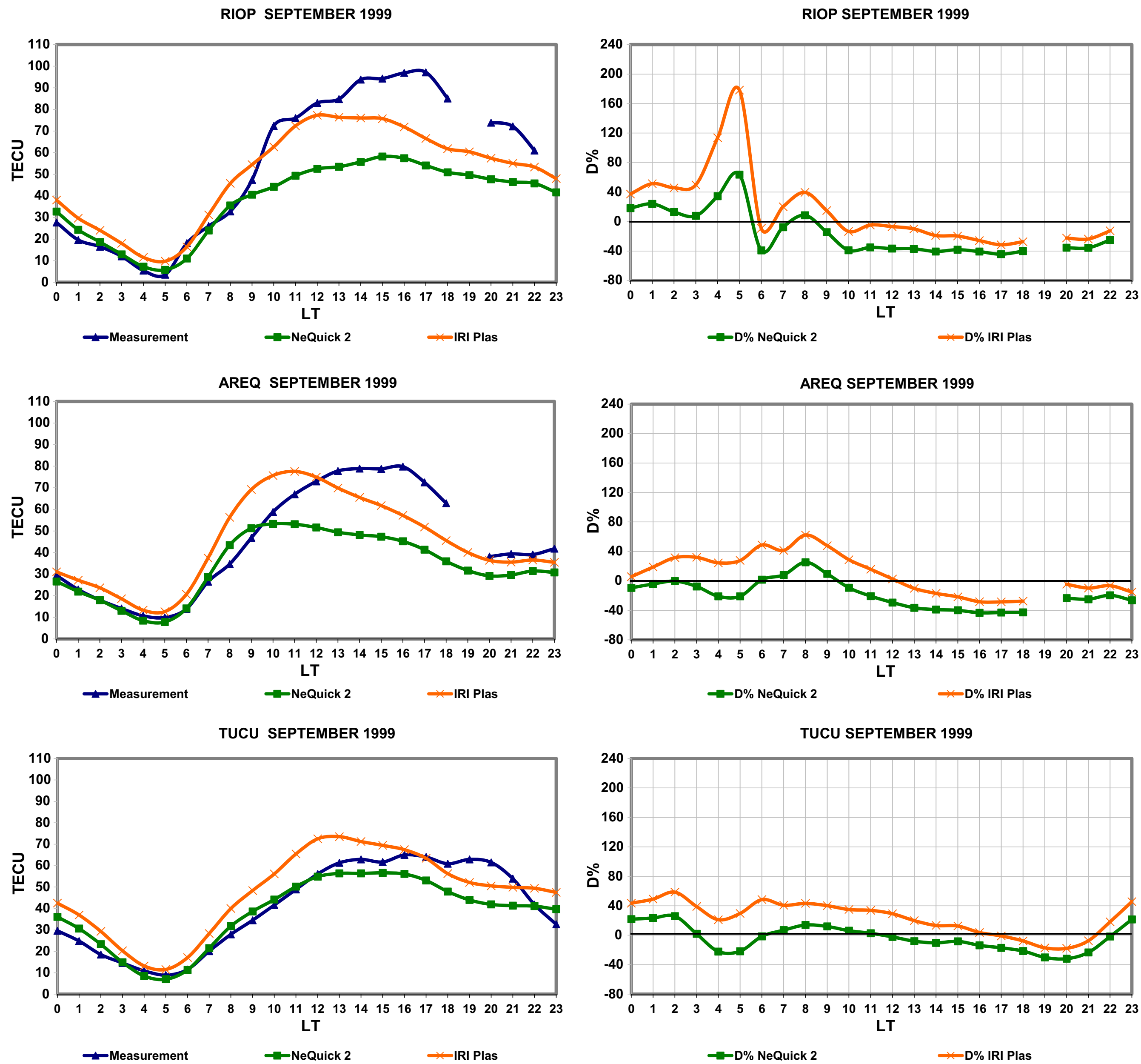

Fig. 6. Modeled and experimental VTEC and D%. Low latitude stations RIOP, AREQ and TUCU. September 1999 (Rz12: 102).

to the measurements than those given by NeQuick2. For the rest of the day IRI Plas overestimates VTEC.

In the top panel of Fig. 6 it can be seen that, for RIOP from 10 to 22 LT, both models give VTEC values lower than the measurements. The underestimation obtained with NeQuick2 is stronger than that obtained with the other model. For 17 LT, NeQuick2 underestimates VTEC in 43 TECU.

For AREQ (middle panel of Fig. 6), NeQuick 2 gives good predictions for the last hours of the night and underestimates VTEC for hours of highest VTEC values. IRI Plas overestimates the electron content from 1 to 11 LT and underestimates it for the rest of the day. Here again, the underestimation obtained with NeQuick2 is stronger than that obtained with the other.

The modeled values obtained with NeQuick2 are better for TUCU, where they are close to the measured VTEC values from 3 to 11 LT (bottom panel of Fig. 6). In general, IRI Plas overestimates VTEC. For 12 LT this model gives a value which is 16 TECU greater than the measured one.

Fig. 7, top panel, shows the results for SANT. It can be seen a good NeQuick2 prediction except from 21 to 2 LT. Moreover, IRI Plas overestimates VTEC for all hours of the day. For RIOG station, middle panel of Fig. 7, both models overestimates the electron content for hours around the maximum reaching a relative deviation close to +30% and +60% with NeQuick2 and IRI Plas, respectively. Similar situation is observed for PALM but the maximum relative deviations for daytime conditions are +20% and +60%. It should be noted that low

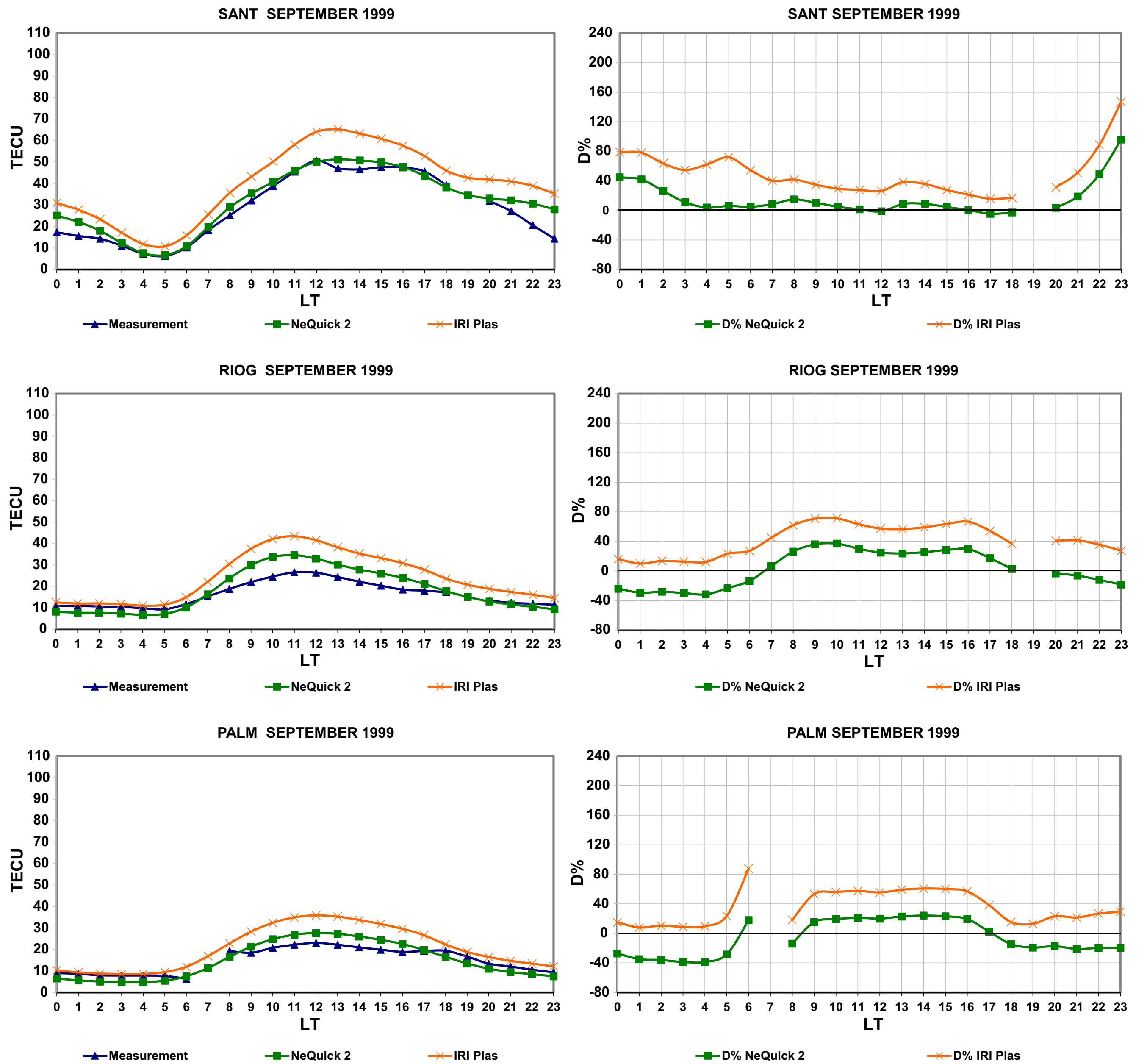

Fig. 7. Modeled and experimental VTEC and D%. Middle and high latitude, stations SANT, RIOG and PALM. September 1999 (Rz12: 102).

GPS-VTEC values obtained for RIOG and PALM cause the relative deviation reaches high value even though the absolute deviation is low (around 3 TECU in the case of NeQuick2)

2.1. Statistical analysis

In order to compare performance of the NeQuick (NeQ) and IRI-Plas models a statistical analysis has been conducted. The aim of this analysis is to contrast the behaviour of both models for different seasons and latitudes, to guide the convenience of using each model for a given scenario. Fig. 8(a) and (b) displays a scatter plot of the full sample of predicted values against observed data for NeQ and IRI Plas respectively. In general, the fitting in both models is quite similar with an R-squared of approximately 85%. However, in Fig. 8(a) dispersion appears to be different than in Fig. 8(b). To assess this observation and statistically compare forecasting errors of the models, we also calculate the respective Root Mean Square Error (RMSE). Based on the RMSE measure, forecast dispersion of NeQ model is higher than that of IRI Plas (11.96 versus 8.85, respectively). This implies that, in general, the IRI Plas model forecasts are more accurate than those from the NeQ.

To further investigate potential differences, a study of the residuals has been done. The residuals are defined as:

$$\text{Residuals} = \text{Modeled value} - \text{Measured value} \tag{7}$$

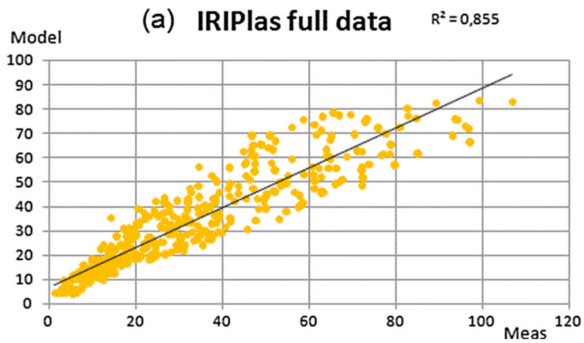

Fig. 8. Scatter plots of predicted vs observed TEC values corresponding to (a) IRI Plas model and (b) NeQuick 2 model. R^2 value is indicated.

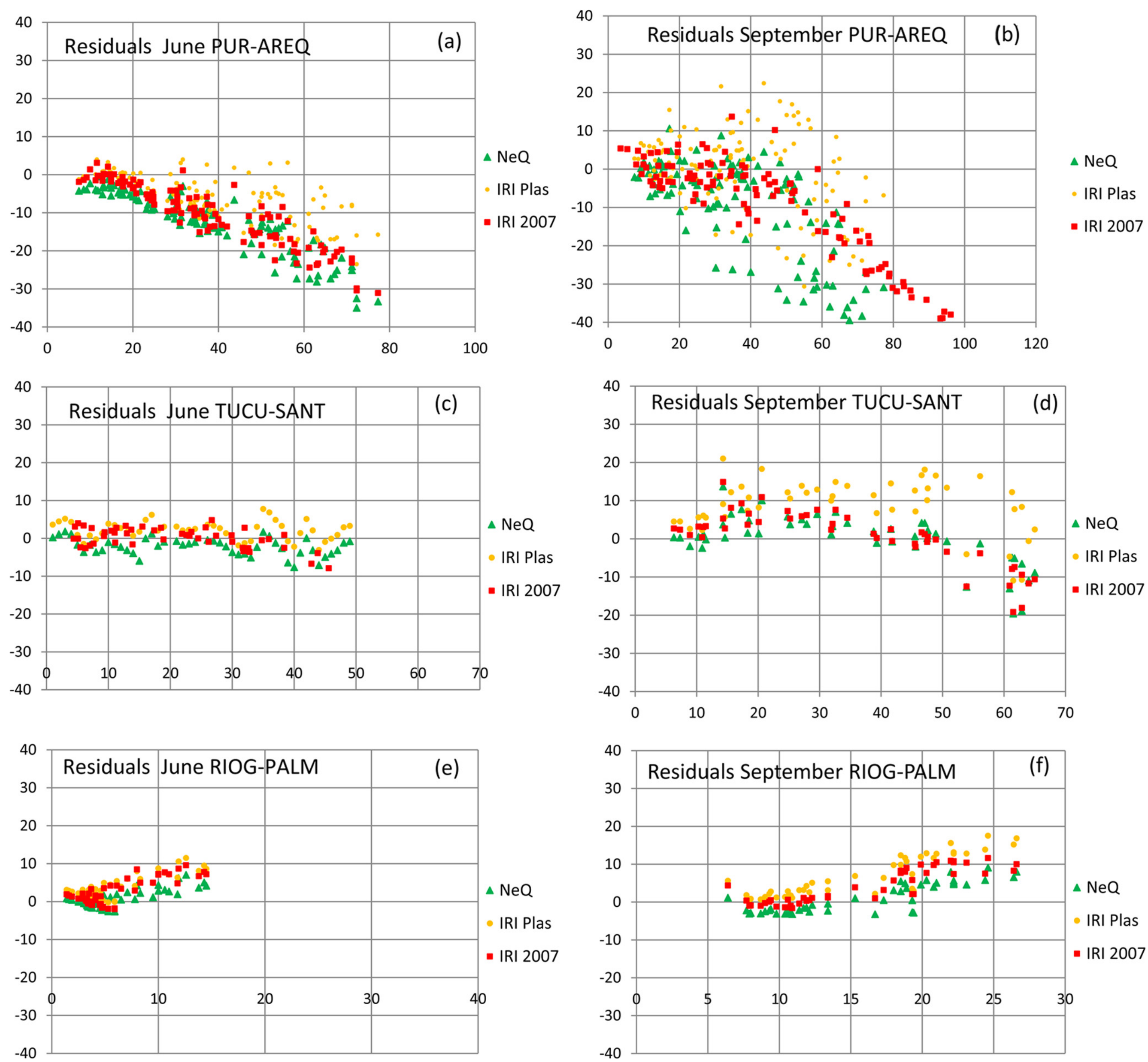

Fig. 9. Residual plots vs observed TEC for equatorial stations: PUR3, BOGT, MARA, RIOP and AREQ, panels (a) solstice and (b) equinox; low latitude stations: TUCU and SANT, panels (c) solstice and (d) equinox and high latitude stations: RIOG and PALM, panels (e) solstice and (f) equinox. Residuals for IRI 2007 are also included.

The stations have been separated by regions of different latitudes. Residuals are plotted against observed data in Fig. 9. The left panel corresponds to June while the right panel to September. Fig. 9(a) and (b) presents the comparison of residuals for the equatorial region (PUR-AREQ), which combines data from the stations PUR3, BOGT, RIOP, and AREQ. Fig. 9(a), shows that while, overall, both models underestimate in the solstice period, the amount of underestimation is higher for the NeQ model. In Fig. 9(b), for equinox, dispersion is higher and the patterns are not as clear as in Fig. 9(a). It can be observed that the NeQ model mostly underestimates, while the IRI-Plas does not display a well-defined pattern. Fig. 9(c) and (d) presents the comparison of residuals for the low latitude region, i.e., TUCU and SANT stations. Fig. 9(c), for solstice, shows slight deviations for both models, with NeQ mostly underestimating and IRI-Plas mostly overestimating. In contrast, Fig. 9(d) shows a more significant overestimation for IRI-Plas. Also, some underestimations for the maximum VTEC values from part of NeQ are observed. Finally, Fig. 9(e) and (f) displays the comparison for high latitudes corresponding to the RIOG and PALM stations. For high latitudes at RIOG and PALM stations, panel (e) of Fig. 9 (solstice) shows a better performance for NeQuick than IRI Plas which gives greater overestimations. This result is also valid during equinox in Fig. 9(f). As expected, larger deviations correspond to higher measured VTEC values.

In summary, although the correlation coefficients of both models are practically the same, IRI-Plas provides better forecasts for the equatorial region while the NeQ is more suitable for low and high latitudes. In general, both models' performances are better for the low latitude region than for the other regions studied.

Comparing the residuals of IRI 2007 with those of IRI Plas, it is generally observed that the underestimates of the previous version of IRI model are greater than those of IRI Plas. In cases where overestimations are observed, those of IRI Plas are greater than those of IRI 2007, except for June in high latitudes (RIOG - PALM) where the residuals of both models are comparable.

3. Discussion and complementary analysis

This work studies the performances of NeQuick2 and IRI Plas models as predictors of VTEC over the low latitude and South American region extending from 18.4°N to −64.7°N for high solar activity. Good agreements and strong discrepancies among predicted and measured VTEC are observed.

For both considered seasons, it is observed that for times of maximum ionization the NeQuick2 behaviour goes from underestimations (as seen in Figs. 2, 3, 5 and 6) to overestimations (Figs. 4 and 7) as we move from the North to the South. This behaviour is also observed for the IRI Plas predictions but only for June solstice. For the September equinox IRI Plas overestimates VTEC for the stations located north of the Northern peak of the equatorial anomaly and then goes from underestimations to overestimations as we move from RIOP to the South.

The comparison of the performance of both models shows that:

(i) For June solstice, the IRI Plas gives better predictions than NeQuick 2 from PUR3 to AREQ, particularly for hours around of minimum VTEC and the rising part of VTEC for PUR3, MARA and AREQ where a good agreement between IRI Plas predictions and measurements is observed. For the stations placed between the Northern peak and the valley of the equatorial anomaly both models underestimate VTEC for hours around the maximum ionization but the performance of IRI Plas is better because the underestimations obtained with NeQuick2 are stronger than those obtained with IRI Plas. The better predictions given by both models correspond to TUCU and SANT. For the two stations with the highest latitude both models overestimate the electron content around the maximum VTEC but the modeled values obtained with NeQuick2 model are closer the measurements than those given by IRI Plas. Summarizing, for June solstice, in general the performance of IRI Plas for low latitude stations is better than that of NeQuick2 and, vice versa, for highest latitudes the performance of NeQuick2 is better than that of IRI Plas. For the stations TUCU and SANT both models have good performance.

(ii) For September equinox, the NeQuick2 gives good predictions for PUR3 and SANT and its performance is better than that of IRI Plas for both stations. For MARA, during hours around the maximum ionization, IRI Plas overestimates VTEC while NeQuick2 underestimates this parameter. For stations placed from the Northern peak to trough of the equatorial anomaly the predictions of NeQuick2 are better than those given by the IRI Plas for hours close to the daily minimum and the ascending part of VTEC, while, on the contrary, for hours of maximum VTEC IRI Plas has a better performance. As for June solstice, the predictions of NeQuick 2 for RIOG and PALM are better than those given by IRI Plas. The performances of the models do not follow a clearly defined pattern as in the other season. However, it can be seen that for the region placed between the Northern peak and the valley of the equatorial anomaly, in general, the performance of IRI Plas is better than that of NeQuick2 for hours of maximum ionization. From TUCU to the South, the best predictions are given by NeQuick2.

3.1. Comparison using foF2 values

The accuracy of an empirical model depends on the availability of reliable data for the specific region and time. An important data source for the ITU-R coefficients used in NeQuick 2 and IRI Plas to calculate NmF2 is the worldwide network of ionosonde stations that has monitored the ionosphere. CCIR maps are most accurate in Northern mid-latitudes because of the high density of stations in this part of the globe. Due to the physical processes mentioned in the introduction of this work, at low latitudes the ionospheric magnitudes show particular behaviours, requiring a high sounding stations density to record and monitor the highly variable ionosphere. Unfortunately low latitude region has rather sparse ionosonde coverage and as a result the models predictions could be less accurate.

To investigate more this point we compare CCIR foF2 values with measurements obtained from the only available ionosonde stations in the region for that period: PRJ18, (18.5°N, 292.9°E; Ramey, Puerto Rico), JI91J, (−12°N, 283.2°E; Jicamarca) and PSJ5J, (−51.6°N, 302.1°E; Port Stanley). Location of the ionosonde stations can be seen in Fig. 1 marked with a triangle.

Even though the ionosondes of Jicamarca and Port Stanley are not exactly in the same location as the GPS stations used in this study, they could give an indication of how the CCIR are determining the frequency peak in that region. Fig. 10 shows the comparison of ionosonde derived monthly median foF2 values in red[1] circles and those obtained with CCIR in blue squares, corresponding to June 1999. Puerto Rico's foF2 values have been manually validated since the automatic scaling presented some differences with the ionograms. It is evident from this figure, that for the station of Puerto Rico, CCIR underestimates constantly ionosonde values by around 1–1.5 MHz, during the available hours. For the station of Jicamarca, the underestimation of CCIR takes place from 7 to 21 LT. In the case of Port Stanley instead, CCIR tends to overestimate during some hours, especially in nighttime. The behaviour shown for June Solstice in terms of foF2 corresponds fairly well to the performance of the models in terms of TEC. In the panels corresponding to PUR3 and AREQ of Figs. 2 and 3 respectively, it can be seen that both models underestimate GPS TEC values, being the NeQuick values the lowest. For southern stations the situation is the reverse, both models overestimate GPS TEC values which correspond to the overestimation of CCIR foF2 values during night hours. However, the overestimation also takes place during day time even though CCIR gives to the models good estimations of foF2 from 10 to 12 LT.

Fig. 11 exhibits foF2 measured and modeled values for the case of September 1999. Comparing the top panels of

[1] For interpretation of color in Fig. 10, the reader is referred to the web version of this article.

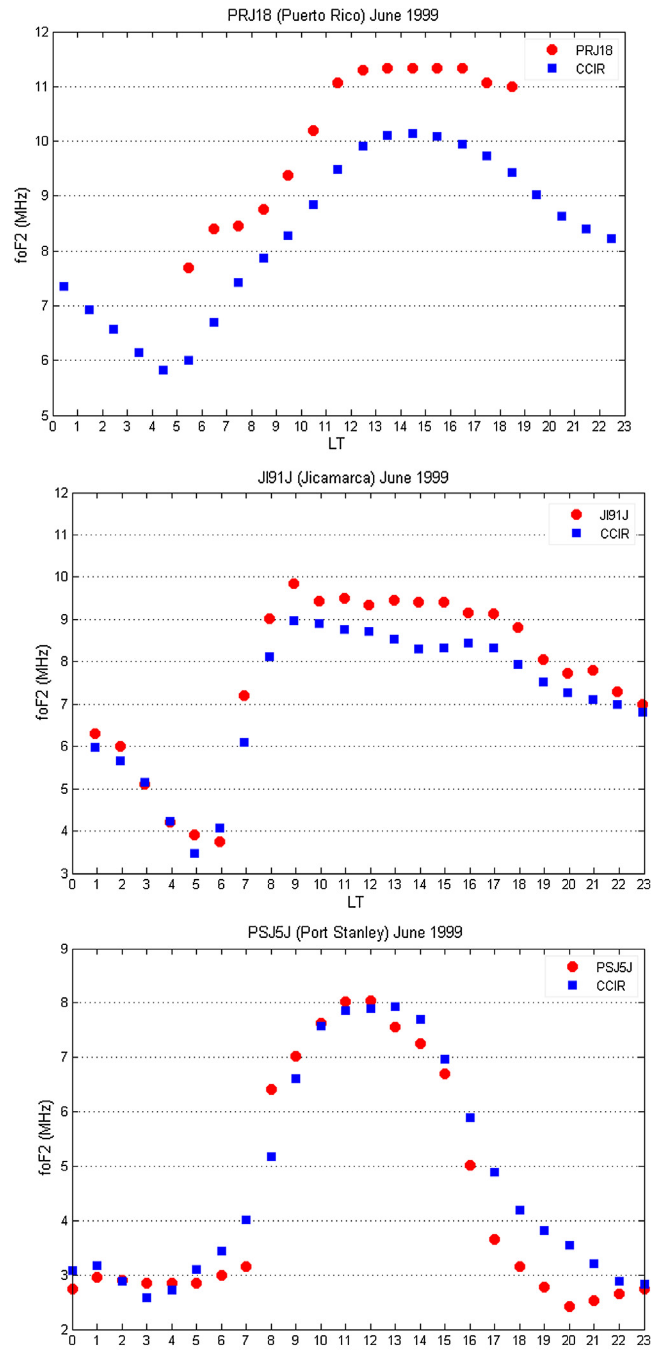

Fig. 10. Modeled (CCIR) and experimental monthly median foF2 values corresponding to June 1999 (solstice) for the stations of Ramey, Jicamarca and Port Stanley.

Figs. 11 and 5 that correspond to Puerto Rico stations, one can observe that NeQuick gives generally good TEC estimates despite the overestimation of about 1 MHz in foF2 from part of CCIR. For the case of Peru stations, even if they are in very different position with respect to the EIA, it can be observed that the NeQuick strong underestimation of TEC values during maximum ionization time corresponds to the underestimation during some hours between 7 to 18 LT from part of CCIR at Jicamarca. For the case of Port Stanley, CCIR overestimates foF2

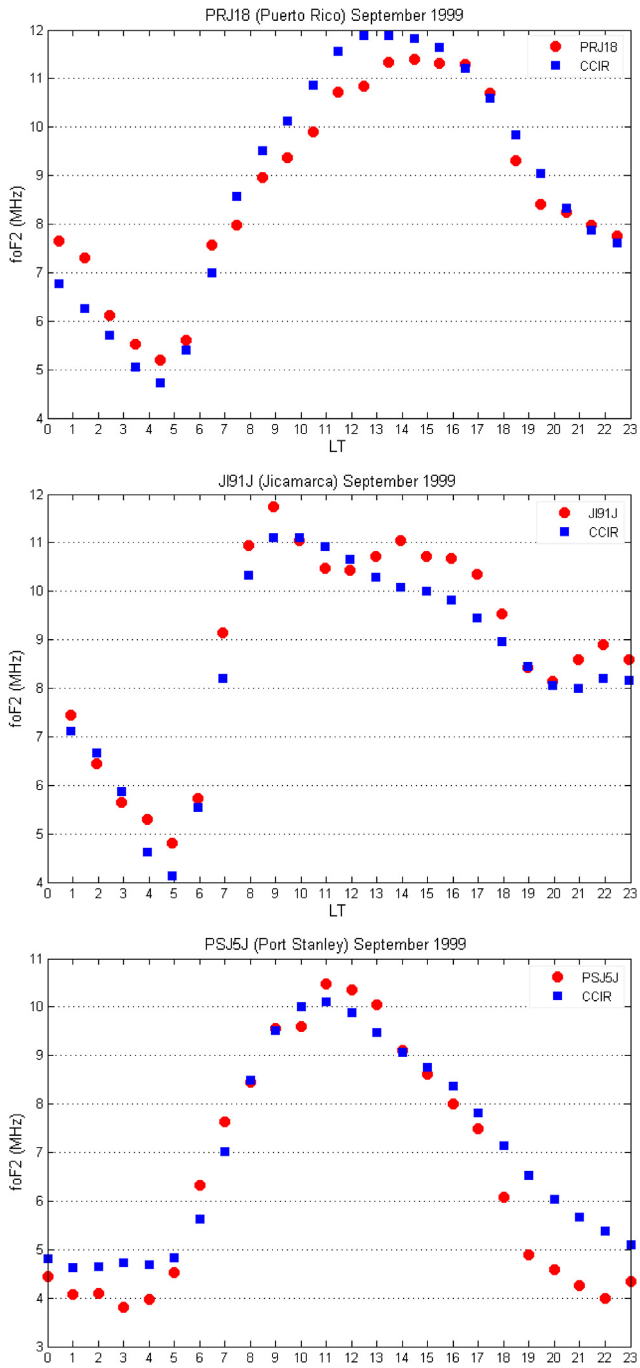

Fig. 11. Modeled (CCIR) and experimental monthly median foF2 values corresponding to September 1999 (equinox) for the stations of Ramey, Jicamarca and Port Stanley.

values during night hours, but when compared with RIOG station the overestimation of NeQuick in TEC is from 8 to 16 LT. It has to be noted that IRI model shows a marked overestimation in all these cases, with exception of AREQ where it underestimates TEC values from 13 LT on. At the stations of Jicamarca and Port Stanley the differences in local time with respect to GPS stations are more evident for this month.

Taking into account that the modeled VTEC is obtained by integrating the vertical electron density, N(h) profile, the observed high discrepancies between predictions and measurements may also be attributed to the inaccurate prediction of the shape of the N(h) profile.

Another possible cause that produces the mentioned discrepancies could be the erroneous prediction of the plasmaspheric contribution to the vertical total electron content. Latitudinal and longitudinal variations of the plasmaspheric contribution to the GPS-VTEC have been reported (Lunt and Kersley, 1999; Balan et al., 2002; Klimenko et al., 2015). The contribution of the plasmasphere to the GPS VTEC is greater at equatorial latitudes than in other latitudes because of the longer path length through the plasmasphere in the equatorial region compared to other latitudes (Yizengaw et al., 2008; Klimenko et al., 2015). Moreover, it has been reported that the plasmaspheric contribution to electron content decreases with increasing latitudes (Lunt et al., 1999).

The overestimations of IRI Plas have been also reported by Cherniak and Zakharenkova (2016). These authors compared NeQuick and IRI Plas models with GPS TEC measurements derived from LEO satellites at different heights. Their results showed that IRI Plas overestimates topside electron densities while NeQuick showed the opposite behaviour during low and moderate solar activities.

In 2014, Venkatesh and collaborators made a comparison of GPS TEC at seven stations around the EIA and IRI and NeQuick empirical models from 2010 to 2013 in the Brazilian sector, and concluded that both models provide comparable simulated values showing underestimation during daytime hours and overestimation during nighttime hours in increased solar activity conditions. Some overestimations from part of IRI were reported for equinox and summer months by these authors. This could be suggesting that the addition of the plasmasphere model in IRI would be causing or accentuating a problem in its topside formulation.

In general, the results of this study suggest that the best calculation of the total electron content over the region placed between the Northern peak and the valley of the equatorial anomaly is obtained with IRI Plas model. While, from TUCU to the highest latitudes, NeQuick 2 gives the best TEC values. For the above exposed, the good performance of IRI Plas around the EIA could be due to a sort of compensation of the integrated density value caused by the plasmasphere adding to the topside or a not smooth enough bond of IRI and SMI models. Concerning to the comparison of both IRI versions, it is generally observed that IRI 2007 gives lower VTEC values than IRI Plas. The contribution of plasmaspheric content, which is not foreseen in the calculations of the IRI 2007 model, could be one of the causes of the underestimations observed in a previous work (Scidá et al., 2012).

4. Conclusions

The performance of NeQuick 2 and IRI Plas models in predicting VTEC up to 20,200 km of altitude for high solar activity over the South American sector has been checked. The obtained results show that: (a) for June solstice, in general the performance of IRI Plas for low latitude stations is better than that of NeQuick2 and, vice versa, for highest latitudes the performance of NeQuick2 is better than that of IRI Plas. For the stations TUCU and SANT both models have good performance; (b) for September equinox the performances of the models do not follow a clearly defined pattern as in the other season. However, it can be seen that for the region placed between the Northern peak and the valley of the equatorial anomaly, in general, the performance of IRI Plas is better than that of NeQuick2 for hours of maximum ionization. From TUCU to the South, the best predictions are given by NeQuick2. A residual analysis showed in general a comparable performance of both models. Residuals separated by regions indicate that models have more problems in predicting TEC values in the stations around the crests of the EIA and better performance at low and high latitudes.

An insight of CCIR foF2 determination confronted with ionosonde derived values could explain with a good approximation the general behaviour and divergence of the models, especially during hours of maximum ionization. The other causes of the differences found could be attributed to (1) an unrealistic shape of the vertical electron density profile and (2) an erroneous prediction of the plasmaspheric contribution to the vertical total electron content; or a combination of these causes, for the considered region and solar conditions. Moreover, in the case of NeQuick, the underestimation trend can be also due to the lack of a proper plasmaspheric model in its topside representation. In contrast, the plasmaspheric model included in IRI, brings on clear overestimations of GPS derived TEC.

Moreover, this study also shown that IRI Plas, in general, gives greater VTEC values than IRI 2007, as expected.

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References

Aggarwal, M., 2011. TEC variability near northern EIA crest and comparison with IRI model. Adv. Space Res. 48 (7), 1221–1231.

Akala, A.O., Seemala, G.K., Doherty, P.H., et al., 2013. Comparison of equatorial GPS-TEC observations over an African and an American station during the minimum and ascending phases of solar cycle 24. Ann. Geophys. 31, 2085–2096.

Anderson, D.N., 1973. A theoretical study of the ionospheric F-region equatorial anomaly, II, results in the American and Asian sectors. Planet. Space Sci. 21, 421–428.

Anderson, D.N., Mendillo, M., Hertniter, B., 1987. A semiempirical low latitude ionospheric model. Radio Sci. 22, 292–306.

Appleton, E.V., 1946. Two anomalies in the ionosphere. Nature 157, 691-691.

Asmare, Y., Kassa, T., Nigussie, M., 2014. Validation of IRI-2012 TEC model over Ethiopia during solar minimum (2009) and solar maximum (2013) phases. Adv. Space Res. 53 (11), 1582–1594.

Balan, N., Otsuka, Y., Tsugawa, T., Miyazaki, S., Ogawa, T., Shiokawa, K., 2002. Plasmaspheric electron content in the GPS ray paths over Japan under magnetically quiet conditions at high solar activity. Earth Planets Space 54, 71–79.

Bent, R. B., Llewelyn, S. K., Nesterczuk, G., et al., 1976. The development of highly successful worldwide empirical ionospheric model its use in certain areas of space communications and world-wide total electron content investigations. Goodman, J. (Ed.). Effect of the Ionosphere on Space Systems and Communications. Springfield, A, pp. 13–28.

Bhuyan, P.K., Borah, R.R., 2007. TEC derived from GPS network in India and comparison with the IRI. Ann. Goephys. 39, 830–840.

Bhuyan, P.K., Hazarika, R., 2013. GPS TEC near the crest of the EIA at 95E during the ascending half of solar cycle 24 and comparison with IRI simulations. Adv. Space Res. 52, 1247–1260.

Bidaine, B., Warnant, R., 2010. Assessment of the NeQuick model at mid-latitudes using GNSS TEC and ionosonde data. Adv. Space Res. 45 (9), 1122–1128. https://doi.org/10.1016/j.asr.2009.10.010.

Bilitza, D., 1990. International Reference Ionosphere. Report NSSDC/WDC-A-R&S 90–22. National Space Science Data Center/World Data A for Rockets and Satellites, pp. 43–77.

Bilitza, D., 2001. International reference ionosphere 2000. Radio Sci. 36 (2), 261–275.

Bilitza, D., Reinisch, B.W., 2008. International reference ionosphere 2007: improvements and new parameters. Adv. Space Res. 42, 599–609.

Bilitza, D., 2009. Evaluation of the IRI-2007 model options for the topside electron density. Adv. Space Res. 44 (6), 701–706.

Bilitza, D., Altadill, D., Zhang, Y., Mertens, C., Truhlik, V., Richards, P., McKinnell, L., Reinisch, B., 2014. The international reference ionosphere 2012 – a model of international collaboration. J. Space Weather Space Climate 4 (A07), 12. https://doi.org/10.1051/swsc/2014004.

Brunini, C., Meza, A., Diaz A., 2001. Regional vertical total electron content using GPS observations. In: Proceedings of the IAG 2001 Scientific Assembly (CD edition), September 2–7, Budapest, Hungary.

Buresova, D., Cander, L.R., Vernon, A., Zolesi, B., 2006. Effectiveness of the IRI-2001-predicted N(h) profile updating with real-time measurements under intense geomagnetic storm conditions over Europe. Adv. Space Res. 37 (5), 1061–1068.

Chasovitin, Yu.K., Gulyaeva, T.L., Deminov, M.G., Ivanova, S.E., 1998. Russian standard model of the ionosphere (SMI). In: Proceedings of the 2nd COST251 Workshop, Side, Turkey, pp. 161–172.

Chauhan, V., Singh, O.P., 2010. A morphological study of GPS-TEC data al Agra and their comparison with the IRI model. Adv. Space Res. 46, 280–290.

Cherniak, I., Zakharenkova, I., 2016. NeQuick and IRI-Plas model performance on topside electron content representation: Spaceborne GPS measurements. Radio Sci. 51, 752–766. https://doi.org/10.1002/2015RS005905.

Chiu, Y.T., 1975. An improved phenomenological model of ionospheric density. J. Atmos. Terr. Phys. 37, 1563–1570.

Coïsson, P., Radicella, S. M., Leitinger, R., Ciraolo, L, 2004. Are models predicting a realistic picture of vertical total electron content? Radio Sci., 39, RS1S14, doi:https://doi.org/10.1029/2002RS002823.

Davies, K., 1990. Ionospheric Radio, IEE Electromagnetic Wave Series 31. Peter Peregrinus Ltd., IEE, London, UK.

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

Ezquer, R.G., de Adler, N.O., Radicella, S.M., González, M.M., Manzano, J.R., 1992. Total electron content obtained from ionogram data alone. Radio Sci. 27, 429–434.

Ezquer, R.G., de Adler, N.O., Heredia, T., 1994. Predicted and measured total electron content at both peaks of the equatorial anomaly. Radio Sci. 29, 831–838.

Ezquer, R.G., López, J.L., Scidá, L.A., Cabrera, M.A., Zolesi, B., Bianchi, C., Pezzopane, M., Zuccheretti, E., Mosert, M., 2014. Behaviour of ionospheric magnitudes of F2 region over Tucumán during a deep solar minimum and comparison with the IRI 2012 model predictions. J. Atmos. Solar – Terrest. Phys. 107, 89–98.

Gulyaeva, T.L., Huang, X., Reinisch, B.W., 2002. Plasmaspheric extension of topside electron density profiles. Adv. Space Res. 29 (6), 825–831.

Gulyaeva, T.L., Bilitza, D., 2012. Towards ISO standard earth ionosphere and plasmasphere model. In: New Developments in the Standard Model. NOVA Publishers, 1, 1–39, ISBN 978-1-61209-989-7 <https://www.novapublishers.com/catalog/product_info.php?products_id=35812>.

Hartman, G.K., Leitinger, R., 1984. Range errors due to ionospheric and tropospheric effects for signals frequencies above 100 MHz. Bull. Geod. 58, 109–136.

Hochegger, G., Nava, B., Radicella, S.M., Leitinger, R., 2000. A family of ionospheric models for different uses. Phys. Chem. Earth, Part C: Solar, Terrest. Planet. Sci. 25 (4), 307–310.

Hunsucker, R.D., Hargreaves, J.K., 2003. The High Latitude Ionosphere and Its Effects on Radio Propagation. Cambridge University Press, United Kingdom.

International Radio Consultative Committee (CCIR), 1967a. Atlas of Ionospheric Characteristics. Report 340, International Telecommunication Union, Geneva.

International Radio Consultative Committee (CCIR), 1967b. Atlas of Ionospheric Characteristics. Report 340–2 (and later suppl.), International Telecommunication Union, Geneva.

Klimenko, M.V., Klimenko, V.V., Zakharenkova, I.E., Cherniak, I.V., 2015. The global morphology of the plasmaspheric electron content during Northern winter 2009 based on GPS/COSMIC observation and GSM TIP model results. Adv. Space Res. 55, 2077–2085.

Klobuchar, J.A., 1987. Ionospheric time-delay algorithm for single-frequency GPS users. IEEE Trans. Aerosp. Electron. Syst. 23, 325–331.

Kumar, S., 2016. Performance of IRI-2012 model during a deep solar minimum and a maximum year over global equatorial regions. J. Geophys. Res. Space Phys. 121, 5664–5674. https://doi.org/10.1002/2015JA022269.

Leong, S.K., Musa, T.A., Omar, K., Subari, M.D., Pathy, N.B., Asillam, M.F., 2015. Assessment of ionosphere models at Banting: Performance of IRI-2007, IRI 2012 and NeQuick 2 models during the ascending phase of solar cycle 24. Adv. Space Res. 55, 1228–1240. https://doi.org/10.1016/j.asr.2014.01.026.

Llewellyn, S.K., Bent, R.B., 1973. Documentation and Description of the Bent Ionospheric Model. AFCRL-TR-73-0657, AD 772733, 133–164, Air Force Cambridge Res. Lab., Bedford, Massachusetts, United States.

Lunt, N., Kersley, L., 1999. The influence of the protonosphere on GPS observations: Model simulations. Radio Sci. 34, 735-732.

Lunt, N., Kersley, L., Bishop, G.J., Mazzella Jr., A.J., 1999. The contribution of the protonosphere to GPS total electron content: experimental measurements. Radio Sci. 34, 1273–1280.

Mahrous, A.M., AbuElezz, O.A., Abdallah, A.M., Fleury, R., 2014. Comparison between the NeQuick Model and VTEC Estimation by GPS Measurements over Egypt, Mitigation of Ionospheric Threats to GNSS: an Appraisal of the Scientific and Technological Outputs of the TRANSMIT Project, Dr. Riccardo Notarpietro (Ed.), ISBN: 978-953-51-1642-4, InTech, doi:https://doi.org/10.5772/58773 <http://www.intechopen.com/books/mitigation-of-ionospheric-threats-to-gnss-an-appraisal-of-the-cientific-and-technological-outputs-of-the-transmit-project/comparison-between-the-nequick-model-and-vtec-estimation-by-gps-measurements-over-egypt>.

McKinnell, L.A., Oyeyemi, E.O., 2009. Progress towards a new global foF2 model for the International Reference Ionosphere (IRI). Adv. Space Res. 43 (11), 1770–1775.

Maltseva, O.A., Mozhaeva, N.S., Nikitenko, T.V., 2015. Comparative analysis of two new empirical models IRI-Plas and NGM (the Neustrelitz Global Model). Adv. Space Res. 55, 2086–2098.

Migoya Orué, Y.O., Radicella, S.M., Coïsson, P., Ezquer, R.G., Nava, B., 2008. Comparing TOPEX TEC measurements with IRI predictions. Adv. Space Res. 42 (4), 757–762.

Mosert, M., Buresova, D., Ezquer, R.G., Mansilla, G., 2004. Behavior of the bottomside electron density profile over Pruhonice. Adv. Space Res. 34 (9), 1982–1989.

Mosert, M., Gende, M., Brunini, C., Ezquer, R., Altadill, D., 2007. Comparisons of IRI TEC predictions with GPS and digisonde measurements at Ebro. Adv. Space Res. 39, 841–847.

Nava, B., Coïsson, P., Radicella, S.M., 2008. A new version of the NeQuick ionosphere electron density model. J. Atmos. Solar-Terrest. Phys., 1856–1862 https://doi.org/10.1016/j.jastp.2008.01.015.

Okoh, D., MsKinnel, L.-A., Cilliers, P., Okere, B., Okonkwo, C., Rabiu, B., 2015. IRI-vTEC versus GPS-vTEC for Nigerian SCINDA GPS stations. Adv. Space Res. 55, 1941–1947.

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

Radicella, S.M., 2009. The NeQuick model genesis, uses and evolution. Ann. Geophys. 52 (3–4), 417–422.

Rawer, K., Ramakrishnan, S., Bilitza, D., 1978. International Reference Ionosphere 1978, International Union of Radio Science, URSI Special Report, 1–75. Bruxelles, Belgium.

Rawer, K. (Ed.), 1984. Encyclopedia of Physics. Geophysics III, Part VII. Springer-Verlag, pp. 389–391.

Reinisch, B., Galkin, I., Huang, X., Vesnin, A., Bilitza, D., 2014. The Ionosphere Real-Time Assimilative Model, IRTAM - A Status Report. EGU General Assembly 2014, held 27 April - 2 May, 2014 in Vienna, Austria, id.3092.

Rishbeth, H., Garriot, O.K., 1969. Introduction to Ionospheric Physics. Academic Press, New York and London.

Scidá, L.A., Ezquer, R.G., Cabrera, M.A., Mosert, M., 2009. IRI 2001/90 TEC predictions over a low latitude station. Adv. Space Res. 44(6), 736–741.

Scidá, L.A., Ezquer, R.G., Cabrera, M.A., Mosert, M., Brunini, C., Buresova, D., 2012. On the IRI 1997 performance as a TEC predictor for the South American sector. J. Atmos. Sol.-Terr. Phys. 81–82, 50–58.

Scidá, L.A., Ezquer, R.G., Cabrera, M.A., Jadur, C., Sfer, A.M., 2016. Tucumán ionospheric model (TIM): initial results for STEC predictions. Adv. Space Res. 58, 821–834.

Tariku, Y.A., 2015. TEC prediction performance of the IRI-2012 model over Ethiopia during the rising phase of solar cycle 24 (2009–2011). Earth, Planets Space 67 (140), 1–10. https://doi.org/10.1186/s40623-015-0312-1.

Venkatesh, K., Fagundes, P.R., Seemala, G.K., de Jesus, R., de Abreu, A. J., Pillat, V.G., 2014. On the performance of the IRI-2012 and NeQuick2 models during the increasing phase of the unusual 24th solar cycle in the Brazilian equatorial and low-latitude sectors. J. Geophys. Res. Space Phys. 119, 5087–5105. https://doi.org/10.1002/2014JA019960.

Yizengaw, E., Moldwin, M.B., Galvan, D., Iijima, B.A., Komjathy, A., Mannucci, A.J., 2008. Global plasmaspheric TEC and its relative contribution to GPS TEC. J. Atmos. Sol.-Terr. Phys. 70, 1541–1548.

Zakharenkova, I.E., Cherniak, Iu.V., Krankowski, A., Shagimuratov, I.I., 2015. Vertical TEC representation by IRI 2012 and IRI Plas models for European midlatitudes. Adv. Space Res. 55, 2070–2076.