Bottom side profiles for two close stations at the southern crest of the EIA: Differences and comparison with IRI-2012 and NeQuick2 for low and high solar activity

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Abstract

Bottom side electron density profiles for two stations at the southern crest of the Equatorial Ionization Anomaly (EIA), São José dos Campos (23.1°S, 314.5°E, dip latitude 19.8°S; Brazil) and Tucumán (26.9°S, 294.6°E, dip latitude 14.0°S; Argentina), located at similar latitude and separated by only 20° in longitude, have been compared during equinoctial, winter and summer months under low (year 2008, minimum of the solar cycle 23/24) and high solar activity (years 2013–2014, maximum of the solar cycle 24) conditions. An analysis of parameters describing the bottom side part of the electron density profile, namely the peak electron density $N_{m}F_2$, the height $h_{m}F_2$ at which it is reached, the thickness parameter $B_0$ and the shape parameter $B_1$, is carried out. Further, a comparison of bottom side profiles and F-layer parameters with the corresponding outputs of IRI-2012 and NeQuick2 models is also reported. The variations of $N_{m}F_2$ at both stations reveal the absence of semi-annual anomaly for low solar activity (LSA), evidencing the anomalous activity of the last solar minimum, while those related to $h_{m}F_2$ show an uplift of the ionosphere for high solar activity (HSA). As expected, the EIA is particularly visible at both stations during equinox for HSA, when its strength is at maximum in the South American sector. Despite the similar latitude of the two stations upon the southern crest of the EIA, the anomaly effect is more pronounced at Tucumán than at São José dos Campos. The differences encountered between these very close stations suggest that in this sector relevant longitudinal-dependent variations could occur, with the longitudinal gradient of the Equatorial Electrojet that plays a key role to explain such differences together with the 5.8° separation in dip latitude between the two ionosondes. Furthermore at Tucumán, the daily peak value of $N_{m}F_2$ around 21:00 LT during equinox for HSA is in temporal coincidence with an impulsive enhancement of $h_{m}F_2$, showing a kind of "elastic rebound" under the action of the EIA. IRI-2012 and NeQuick2 bottom side profiles show significant deviations from ionosonde observations. In particular, both models provide a clear underestimation of the EIA strength at both stations, with more pronounced differences for Tucumán. Large discrepancies are obtained for the parameter $h_{m}F_2$ for HSA during daytime at São José dos Campos, where clear underestimations made by both models are observed. The shape parameter $B_0$ is quite well described by the IRI-2012 model, with...
very good agreement in particular during equinox for both stations for both LSA and HSA. On the contrary, the two models show poor agreements with ionosonde data concerning the shape parameter $B_1$.

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Keywords: Bottom side electron density profiles; IRI and NeQuick2 model; $B_0$ and $B_1$ parameters; EIA longitudinal variability

1. Introduction

The ionospheric electron density at equatorial and low latitudes shows significant variations with time, season, latitude and altitude due to complex electrodynamic phenomena (e.g., Stening, 1992; Reinisch and Huang, 1996; Heelis, 2004; Lee et al., 2008; Venkatesh et al., 2014a). In particular, at low latitudes and along the geomagnetic equator, the ionosphere shows a significant variability due to the dominant phenomenon of the Equatorial Ionization Anomaly (EIA) (e.g., Lyon and Thomas, 1963; MacDougall, 1969; Balan and Iyer, 1983; Batista and Abdu, 2004; Abdu et al., 2008), also called Appleton anomaly (Appleton, 1946), linked to the equatorial fountain effect (Martyn, 1955; Duncan, 1960; MacDougall, 1969; Balan and Iyer, 1983; Batista and Abdu, 2004; Abdu et al., 2008). As described by Abdu et al. (2008), during the day the development of the EIA is generated by the E-region dynamo zonal electric field, linked to the Equatorial Electrojet (EEJ), which gives rise to an \( E \times B \) plasma vertical drift leading to the aforementioned plasma fountain effect. As discussed by Martyn (1955) and Duncan (1960), ionization is uplifted over the magnetic equator and diffuses down the geomagnetic lines of force, under pressure gradient and gravity forces (Stening, 1992), modifying the electron density concentrations at low latitudes where the F-region plasma increases, thus forming the electron density crests on both sides (north and south) of the magnetic equator (at about \( \pm 15-18^\circ \) geomagnetic latitude) (Lyon and Thomas, 1963). Consequently, the scenario of the equatorial and low latitude ionospheric F-region is the following: F-region is lifted up at the magnetic equator, with a decrease of the peak density, while the F-region peak density increases at the crests of the anomaly (Batista and Abdu, 2004). The persistence of the EIA at nighttime hours, depending on the season and solar activity, is known to be produced by the post sunset enhancement in the eastward electric field generated by the F-region dynamo action (Chuo, 2012). This dynamo action, in turn, results from the eastward component of the thermospheric wind blowing in the region of the decreasing dawn-to-dusk E-layer Pedersen conductivity distribution (Heelis, 2004).

Owing to these particular conditions, the equatorial and low-latitude ionosphere show a strong spatio-temporal variability making the modeling of the ionospheric parameters particularly difficult.

The International Reference Ionosphere (IRI) (Bilitza, 2001; Bilitza and Reinisch, 2008; Bilitza et al., 1990, 2014, 2017) is an empirical model for the description of the ionosphere. It is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI), based on an extensive database and able to capture much of the repeatable characteristics of the ionosphere such as the electron density, the electron content, the electron temperature and the ion composition, as a function of height, location, and local time for quiet and storm-time periods (Araujo-Pradere et al., 2011, 2013; Zakharenkova et al., 2013). The IRI model was first developed in 1978 (Rawer et al., 1978) and thereafter several updated versions have been released, with IRI-2012 (Bilitza et al., 2014) and IRI-2016 (Bilitza et al., 2017) representing the most recent ones.

The NeQuick2 model (Nava et al., 2008) is the second version of NeQuick, an empirical ionospheric model being widely used for the estimation of electron density profiles and related parameters. The model was developed at the International Centre for Theoretical Physics (ICTP) and has been adopted by the International Telecommunication Union (ITU) for TEC modeling (ITU, 2003). Its outputs have been validated by several workers who reported a good agreement at mid latitudes and improved performances while assimilating measurements (Jodogne et al., 2005; Bidaine and Warnant, 2010).

The characterization of the ionospheric F-region represents a central aim owing to the fact that the corresponding electron density provides the main contribution to the Total Electron Content (TEC) that largely affects radio wave propagations (Asmare et al., 2014). Knowledge of the spatial distribution of the electron density in the ionosphere, especially the ionospheric profile \( N(h) \), is crucial for HF telecommunication, ionospheric tomography, GNSS operations and ionospheric studies. Such representation is also useful in practical space weather applications and for modeling various physical processes in the ionosphere (Chuo, 2012).

In particular, the study of the bottom side profile, that represents the electron density distribution under the F2-layer peak, is of primary importance to improve the model reliability and consequently the efficiency of radio communications. The F2-layer bottom side electron density profile can be well described by means of the maximum electron...
density $N_{m}F_2$, the height $h_{m}F_2$ at which it is reached, the thickness parameter $B_0$ and the shape parameter $B_1$ (Chuo, 2012). $N_{m}F_2$ represents the absolute maximum electron density in the profile and is linked to the critical frequency of the $F_2$-layer $f_{o}F_2$ by the relation $N_{m}F_2 = 1.24 \cdot 10^{10} (f_{o}F_2)^2$, with $N_{m}F_2$ expressed in $m^{-3}$ and $f_{o}F_2$ in MHz; $f_{o}F_2$ individuates the maximum frequency reflected by the ionosphere for a vertical travelling wave. The bottom side thickness parameter $B_0$ is defined as the difference between $h_{m}F_2$ and the height where the electron density equals to 0.24 times $N_{m}F_2$, in the absence of the $F_1$-layer or the $F_1$-peak height $h_{m}F_1$, if the latter occurs. The shape parameter $B_1$ describes the shape of the profile between the two heights from which $B_0$ is estimated (Reinisch and Huang 1996; Bilitza et al., 1998).

The solar activity represents the main controller of the ionospheric variability. The minimum of the cycle 23/24 (deep low solar activity for the years 2008–2009), was the longest and quietest since the advent of space-based measurements (Liu et al., 2011). During the period from January 2008 to December 2009, 527 spotless days have been observed, while they were 226 and 176 for the minimum 22/23 (years 1996–1997) and 21/22 (years 1986–1987) respectively; the magnetic field at the solar poles was approximately 40% weaker than that of cycle 22/23 (Araujo-Pradere et al., 2011). Measurements by the Ulysses spacecraft revealed a 20% drop in solar-wind pressure since the mid-1990s, the lowest point since the start of such measurements in the 1960s (Phillips, 2009). Moreover, Chen et al. (2011, 2012) found a decrease of ~15% in the EUV solar radiation for the last solar minimum in comparison to the previous one. This decrease explains the lower values of $f_{o}F_2$ observed by ionospheric stations all around the world (Liu et al., 2011; Chen et al., 2011; Bilitza et al., 2012). In such particular conditions, problems in model predictions have been discussed by several works (e.g., Heelis et al., 2009; Coley et al., 2010; Lühr and Xiong, 2010; Bilitza et al., 2012).

The years 2013–2014, representing the maximum of the solar cycle 24, have been characterized by a low solar activity in comparison to the previous maxima. A yearly sunspot average of 65 and 113 for the years 2013 and 2014 have been registered respectively. To find a maximum with such a low activity it is necessary to turn back to solar cycle 12 that registered respectively 90 and 102 sunspot yearly averages for 1906 and 1907 respectively. Hence, the minimum of the solar cycle 23/24 and the maximum of the cycle 24 provide two very interesting natural windows to study the ionospheric plasma response to such particular solar activity conditions.

The characteristics of the bottom side profiles have been largely studied (e.g., Aggarwal et al., 1996; Sethi and Pandey, 2001; Batista and Abdu, 2004; Bertoni et al., 2006; Zhang et al., 2004, 2008; Chen et al., 2006; Sethi et al., 2007, 2009; Altadill et al., 2009; de Jesus et al., 2011; Chuo, 2012; Lee and Reinisch, 2012; Venkatesh et al., 2014a; Venkatesh and Fagundes, 2016), showing variations with the season, solar activity level, and day-to-night alternation.

As mentioned, the equatorial and low-latitude ionosphere show very particular behaviors due to the dominant phenomenon of the EIA. In particular, the EIA crests in the South American sector, owing to the curvature of the magnetic equator, represent very complex regions that strongly distinguish them from the other ones. Recently, Fagundes et al. (2016) analyzed vTEC values inferred from two latitudinal chains (~15–20° separated in longitude) of GPS-TEC stations from equatorial region to low latitudes in the East and West Brazilian sectors under the geomagnetic disturbed conditions of the extreme space weather event of 17–18 March 2015. They found that the EIA was very disturbed during the storm main phase, with vTEC values from the equator to beyond the EIA crests much more disturbed in the West sector than in the East one. This difference between very close longitudinal sectors has been observed for the first time and strongly suggests that relevant longitudinal-dependent EIA variations in the South American region can occur. Hence, it is of significant importance to have a clear description of the EIA pattern and dynamics in South America for both quiet and disturbed geomagnetic conditions.

In this work, bottom side electron density profiles and associated parameters from two closely spaced ground-based ionosondes, namely São José dos Campos (23.1°S, 314.5°E, dip latitude 19.8°S; Brazil) and Tucumán (26.9°S, 294.6°E, dip latitude 14.0°S, Argentina), located upon the southern crest of the EIA at similar latitude and only 20 degrees separated in longitude, have been compared for the very low solar activity year 2008 (sunspot annual average $R = 3$) and the high solar activity years 2013 and 2014 (sunspot annual average $R = 65$ and 113 respectively), under quiet geomagnetic conditions. A comparison with IRI-2012 and NeQuick2 models is also carried out for both bottom side profiles and the parameters that characterize them. Moreover, a comparison with IRI-2012 gives us the possibility to test the performances of the recent ‘ABT-2009’ option available for this version of the model.

The main objectives of the study are: (1) to make a comparison of bottom side profiles at two close stations upon the southern crest of the EIA in the South American sector, in order to improve our knowledge about the spatial pattern of the EIA in this very particular region and to detect possible relevant longitudinal-dependent variations under quiet geomagnetic conditions; (2) to detect differences between low and high solar activity levels; (3) to test the performance of IRI-2012 and NeQuick2 models.

2. Dataset and analyses

The ionosonde data from São José dos Campos (SJ) and Tucumán (TU) have been analyzed during the minimum of the solar cycle 23/24 and the maximum of the solar cycle 24. Fig. 1 shows the locations of the two stations, along with the constant main field inclination lines (red for posi-
tive inclination, blue for negative inclination) and the geographic latitude and longitude.

In São José dos Campos a Canadian Advanced Digital Ionosonde (CADI) is operational and located at the UNIVAP (Universidade do Vale do Paraíba) since August 2000. The digital ionosonde antenna is a double delta dipole array supported by a 20 m tower, where one of the dual antennas is used for transmitting and the other one is used for receiving (Grant et al., 1995; MacDougall et al., 1997). The ionospheric measurements at Tucumán began in 1957, the International Geophysical Year, when an analog ionosonde was transferred from the Navy of Argentina to the National University of Tucumán which was stopped working in 1987 (Ezquer et al., 2014). In August 2007, an AIS-INGV (Zuccheretti et al., 2003) was installed at the Upper Atmosphere and Radio Propagation Research Center of the Regional Faculty of Tucumán of the National Technological University (UTN).

Ionograms for the considered locations have been manually scaled to derive the parameters of interest. $N_{m}F_2$ values have been calculated through the relationship $N_{m}F_2 \left[ m^{-3} \right] = 1.24 \times 10^{10} (f_{o}F_2 \left[ MHz \right])^2$, using manually scaled

Fig. 1. Map of the geomagnetic field inclination in the South American sector, with displayed the ionosonde locations of SJ and TU. Red lines indicate positive inclination, while blue lines indicate negative inclination. Geographic latitudes and longitudes are also indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
foF2 values that have been validated according to the International Union of Radio Science (URSI) standard (Wakai et al., 1987). Bottom side electron density profiles and the parameter hmF2 have been obtained applying the POLAN (POLynominal ANalysis) true height inversion algorithm (Titheridge, 1985) to every ionogram. This procedure provides a very robust and reliable dataset for the parameter NmF2, while both bottom side profiles and hmF2 values can be interested by inaccuracy when an E-valley occurs along the profile.

The IRI electron density distribution below the F2-peak is given by the analytical function (Ramakrishnan and Rawer, 1972)

\[ N(h) = NmF2[\exp(-x^B)] \times \cosh(x), \]

\[ x = (hmF2 - h)/B_0. \]

Eq. (1) has been fitted for the bottom side electron density profiles derived from ionosondes to calculate the corresponding bottom side thickness (B) and shape (B) parameters.

Bottom side profiles and modeled B0 and B1 from IRI-2012 have been obtained running the on-line model (http://omniweb.gsfc.nasa.gov/vitmo/iri2012_vitmo.html) using the option “ABT-2009” (Altadill et al., 2009). Altadill et al. (2009) obtained an improvement of 40% and 20% in B0 and B1 prediction of IRI respectively; therefore, IRI has been run selecting the “ABT-2009” option for the bottom side part of the profile, and the “NeQuick” option for the topside part of the profile. For the F-peak model, the International Radio Consultative Committee (CCIR) coefficients (1967a, 1967b) were preferred to the Union of Radio Science (URSI), since the CCIR coefficients are recommended for locations on the continents (Rush et al., 1989). Furthermore, Bertoni et al. (2006) compared NmF2 and hmF2 from IRI-2001 with ionosonde values in the South American sector and found lower differences using CCIR coefficients than the URSI ones. Lee et al. (2008) also obtained similar results for the station of Jicamarca (12°S, 77°W; Peru).

To describe the electron density of the ionosphere above 90 km and up to the peak of the F2-layer, the NeQuick2 model uses a modified DGR profile formulation (Di Giovanni and Radicella, 1990), which includes five semi-Epstein layers (Rawer, 1982) with modeled thickness parameters (Radicella and Zhang, 1995). Three profile anchor points are used: the E-layer peak, the F1-layer peak and the F2-layer peak, modeled in terms of the ionosonde parameters foE, foF1, foF2 and M(3000)F2. The model uses the expression NmF [m^-3] = 1.24 \times 10^{10} (foF [MHz])^2 for the peak electron densities (being A = E, F1 or F2), sets hmF = 120 km and hmF = (hmF + hmF)/2, with hmF calculated using the Dudeney formula (Dudeney, 1978, 1983), and expresses the bottom side profile as follows (Nava et al., 2008):

\[ N_{\text{bottomside}}(h) = N_E(h) + N_{F1}(h) + N_{F2}(h), \]

where

\[ N_E(h) = \left( \frac{4NmE}{1 + \exp \left( \frac{h - hmE}{B_E} \right)} \right) \exp \left( \frac{h - hmE}{B_E} \right), \]

\[ N_{F1}(h) = \left( \frac{4NmF1}{1 + \exp \left( \frac{h - hmF1}{B_{F1}} \right)} \right) \exp \left( \frac{h - hmF1}{B_{F1}} \right), \]

\[ N_{F2}(h) = \left( \frac{4NmF2}{1 + \exp \left( \frac{h - hmF2}{B_{F2}} \right)} \right) \exp \left( \frac{h - hmF2}{B_{F2}} \right), \]

\[ NmE = NmF1 - NmF2. \]

with BE, BF1 and BF2 that express the thickness parameters (in km) for the layers E, F1 and F2, respectively.

The NeQuick2 profiles for the present work have been obtained running the on-line version of the model (http://t-ict4d.ictp.it/nequick2/nequick-2-web-model). B0 and B1 have been obtained fitting the profiles with relations (1) and (2). Nevertheless, as shown by comparing Eqs. (1) and (2) with Eqs. (3) and (4), NeQuick2 uses a different formulation than IRI for the electron density distribution below the F2-peak, so the comparison for these two parameters has to be considered only qualitative.

During both periods of low and high solar activity, after preliminary considerations about the availability of data for both ionosondes, one month has been chosen as representative for every season (equinox, summer and winter) to discuss the diurnal and seasonal characteristics of bottom side profiles (and associated parameters NmF2, hmF2, B0 and B1), and to compare them with IRI-2012 and NeQuick2 ones. The selected months with the corresponding monthly average sunspot number are reported in Table 1. Selecting September for LSA and March for HSA to represent the equinox season, we assume that differences/asymmetries occurring between these two months do not alter the results of the analyses. Furthermore, only

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<td>Monthly mean sunspot number for the months selected to represent the low and high solar activity periods.</td>
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quiet geomagnetic conditions have been taken into account, selecting for each month the 10 geomagnetic quietest days, by virtue of the geomagnetic information from the GFZ German Research Centre for Geosciences. Specifically, the quietest days are chosen on the basis of criteria linked to the geomagnetic Kp index; a detailed description of how the quietest/most disturbed days are selected and related data are both available at http://www.gfz-potsdam.de/en/section/earths-magnetic-field/data-products-services/kp-index/qd-days/. Finally, the comparison between ionosonde measurements, and IRI-2012 and NeQuick2 outputs, for the parameters $N_m F_2$, $h m F_2$, $B_0$ and $B_1$, is carried out calculating averages over the 10 quietest days selected for every month.

3. Results and discussion

3.1. Bottom side electron density profiles

Figs. 2 and 3 show examples of bottom side electron density profiles from ionosonde, IRI-2012 and NeQuick2 for SJ and TU, respectively. In these figures, the panels on the left side show the results for low solar activity (LSA) while the panels on the right side display the results for high solar activity (HSA). The first row reports equinoctial profiles (September 2008 and March 2014), the second row reports winter profiles (June 2008 and August 2014) and the third row reports summer profiles (December 2008 and December 2013). After choosing a

![Fig. 2. Bottom side electron density profiles from ionosonde (black), IRI-2012 (red) and NeQuick2 (blue) for the station of São José dos Campos. Profiles for low solar activity (LSA, on the left) and high solar activity (HSA, on the right) for equinoctial (first row), winter (second row) and summer (third row) season for the 07 LT (first column for LSA and HSA), 13 LT (central column) and 19 LT (right column) are displayed. The data at which every profile refers is also indicated on the top side of every panel. The x axis for the electron density is logarithmic. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image-url)
definite day for every season, three different hours, 07 LT (left column), 13 LT (central column) and 19 LT (right column), have been plotted for both LSA and HSA. The same days are displayed for both stations.

Considering preliminary inter-station differences that will be deeply analyzed in Section 3.2.1, the ionosonde profiles show comparable variations with the hour of the day, season and solar activity for SJ and TU. Under the effect of the EIA, more specifically under the effect of the pre-reversal enhancement, at the crests of the anomaly the daily maximum of the peak electron density is expected around sunset hours (19 LT) (Heelis, 2004). Venkatesh et al. (2014b) found the following characteristics for the EIA in the Brazilian sector: (1) the strength of the anomaly crest is more pronounced for HSA than for LSA; (2) it reaches the maximum strength during equinox for HSA; (3) the EIA is not well developed in winter; (4) it is clearly observed in summer for HSA and only barely visible during equinoctial and summer seasons for LSA. At SJ station, for HSA in summer and equinox, a comparable value of $NmF2$ is reached at 13 LT and 19 LT. At TU, higher values at 19 LT than 13 LT are observed during equinox (for both LSA and HSA) and in winter for HSA. In general, comparable electron density values are observed for the two stations during winter and summer seasons, for both LSA and HSA. On the contrary, relevant differences appear for HSA during equinox, for which more pronounced electron density values are measured at TU, in particular at 13 and 19 LT.

A comparison of electron density profiles from ionosonde with the ones inferred by IRI-2012 and NeQuick2 shows differences between observations and models. Better agreements with ionosonde profiles are observed for LSA than HSA, with the best agreement in particular for LSA at 07 LT. It is appreciable how both IRI-2012 and NeQuick2 underestimate the measured values of the peak

Fig. 3. Same as Fig. 2 for the station of Tucumán.
electron density over SJ and TU at 19 LT during equinox for LSA. For the same season, for HSA, the $NmF2$ value measured at both stations is slightly underestimated by IRI-2012, while NeQuick2 provides a good correspondence at SJ and an underestimation at TU. During summer season, both IRI and NeQuick2 underestimate the parameter $NmF2$ at 07 LT for LSA at both stations. Moreover, it is worth noting that, for both SJ and TU both models provide a clear $hmF2$ underestimation at 13 LT for LSA and at 13 and 19 LT for HSA.

Sethi and Pandey (2001) compared the incoherent scatter observations of bottom side electron density profiles with the outputs of IRI-95 for midday hours (10:00–14:00 LT), in summer, winter and equinox, for the solar maximum year of 1981 at the low-latitude station of Arecibo (18.4°N, 66.7°W; Puerto Rico). They reported good correspondences in winter with an underestimation of the electron density at the F1-layer height range. Furthermore, an IRI-95 overestimation is reported in summer and equinox at all heights. In the present study, Figs. 2 and 3 show that the electron density is overestimated by IRI-2012 around midday in winter for HSA at all heights, at both ionosonde stations. Both models show a tendency to overestimate electron density values below heights of ~250 km at 13 LT for HSA and it is interesting to note that NeQuick2 seems to work generally better than IRI-2012 in this height range. Aggarwal et al. (1996) made a comparison between ionosonde bottom side profiles and IRI-90 at New Delhi (28.6°N, 77.2°E; India), near the northern crest of the EIA. The comparison was extended to low, mid and high solar activity (years 1958–1959, 1964–1965 and 1968–1969), for equinox, summer and winter, considering profiles around the local midday. Their results show an IRI-90 overestimation during equinox and summer in every condition of solar activity; in winter, a good agreement is found for LSA, with an underestimation for HSA. Considering the profiles below ~250 km at 13 LT, where the IRI-2012 model shows a tendency to the overestimation for both SJ and TU, in particular for HSA, the results are in accordance with those reported by Aggarwal et al. (1996).

Finally, profiles in Figs. 2 and 3 suggest that both models provide better results for the very particular period of low solar activity of the last minimum than for the high solar activity of the recent solar maximum, with better performances for the SJ ionosonde. Preliminary considerations reported in this section about the comparison between ionosonde bottom side profiles and IRI-2012 and NeQuick2 outputs will be deeply examined in Sections 3.2.2 and 3.3, by discussing also monthly average values of some parameters that characterize the bottom side electron density profile.

3.2. F-layer peak parameters $NmF2$ and $hmF2$

3.2.1. Pattern and inter-station comparison

In order to study in detail the inter-station differences, Figs. 4 and 5 display monthly averages of $NmF2$ and $hmF2$, derived from SJ and TU ionosondes, with the corresponding standard deviations. The results for LSA are on the left, while those for HSA are on the right. In every panel, the season, the month and the year are shown. In the bottom side part of every panel, $NmF2$ and $hmF2$ inter-station differences are displayed. The differences are defined as $\Delta NmF2 = NmF2_{TU} - NmF2_{SJ}$ and $\Delta hmF2 = hmF2_{TU} - hmF2_{SJ}$, being $NmF2_{TU}$ (or $hmF2_{TU}$) and $NmF2_{SJ}$ (or $hmF2_{SJ}$) monthly average values for TU and SJ, respectively.

As mentioned, SJ and TU are two stations located upon the southern crest of the EIA at similar latitude and only 20 degrees separated in longitude. For these reasons, it is very interesting to study whether the longitudinal differences found by Fagundes et al. (2016) under geomagnetic disturbed conditions are observed also under the quiet geomagnetic conditions considered in this work. A priori, climatological patterns strongly affected by the EIA are expected.

As expected, Fig. 4 shows higher $NmF2$ values for HSA than for LSA, for both SJ and TU. This aspect is particularly clear during nighttime hours for equinox season where LSA/HSA excursion as high as $\sim 3.0 \times 10^{12}$ [m$^{-3}$] and $\sim 2.5 \times 10^{12}$ [m$^{-3}$] can be reached at TU and SJ, respectively. For LSA, higher and lower values at both stations are observed in summer and winter respectively, confirming the findings by Ezquer et al. (2014) who reported that the semi-annual anomaly was not observed during the last solar minimum at TU. Furthermore, a very similar diurnal trend is observed at SJ and TU for the three seasons, with differences always within one standard deviation. On the contrary, for HSA significant inter-station differences are observed during equinox with no relevant differences in summer and winter. In detail, during equinox a daily minimum at 06:00 LT and a pronounced maximum around 21:00 LT are reached, with high values that persist during pre-midnight and nighttime hours until 02:00 LT at both stations. Nevertheless, the most important feature is that higher $NmF2$ values are observed at TU than at SJ, with significant differences registered between 18:00–23:00 LT, for which an average value of $\sim 1.5 \times 10^{12}$ [m$^{-3}$] is measured.

The $NmF2$ maximum around 21:00 LT during equinox for HSA, observed both at SJ and TU, represents a typical feature of the EIA intensification due to the pre-reversal enhancement in the vertical drift. In fact, the maximum strength of the EIA is observed during equinox for HSA in the South American sector. The pronounced inter-station differences found during this period suggest that near the crests of the EIA, different patterns in the electron density can be observed also for very close longitudinal sectors. The present study shows that the effect of EIA appears much more pronounced at TU than at SJ during equinox for HSA, when the EIA reaches its maximum strength. According to the results reported by Fagundes et al. (2016) during disturbed conditions, the present study confirms that the EIA effect is stronger in the West sector.
than in the East one in the South American region also during quiet geomagnetic conditions.

The results for hmF2 are presented in Fig. 5 and show, as previously reported for NmF2, higher values for HSA...
than for LSA. During LSA, in winter and equinox, daily trends are quite flat with values between 200 and 350 km for both stations. In these seasons, significant differences appear only during winter between 22:00–06:00 LT with higher values at TU and an average difference of ~50 km. During summer, the daily $h_mF_2$ pattern at SJ and

Fig. 5. Same as Fig. 4 but for $h_mF_2$. 
TU is similar, characterized by two minima around sunrise (07:00 LT) and sunset (18:00 LT), an increase during daytime and a daily peak around midday; significant interstation differences are however present between 00:00–04:00 LT, with higher values at TU. For HSA, the following relevant differences have been found: (1) in winter around midday lower values at TU than at SJ; (2) in summer around 21:00–22:00 LT, higher values at TU than at SJ; (3) during equinox between 19:00–21:00 LT, an impulsive $hmF_2$ increase characterizing TU is not observed at SJ, with a peak difference of ~84 km reached at 20:00 LT.

As previously mentioned in the results for $NmF_2$, the EIA is particularly strong for HSA during equinox and more pronounced at TU than at SJ. It is interesting to note that during equinox the high values of $NmF_2$ in the pre-midnight hours for HSA (Fig. 4) are linked with different $hmF_2$ patterns observed at the two stations: at SJ a slightly decrease of $hmF_2$ from daytime values is observed, with a constant value during nighttime ($hmF_2 \sim 300 \text{ km}$); at TU, where the $NmF_2$ increase is very pronounced, $hmF_2$ shows an impulsive increase that starts around 17:00 LT ($hmF_2 \sim 300 \text{ km}$), reaches a peak value ($hmF_2 \sim 430 \text{ km}$) in correspondence of the $NmF_2$ peak at 21:00 LT, and then starts decreasing till around midnight. Therefore, at TU the EIA produces an increase of the local electron density associated with a kind of “elastic rebound” between 17:00–00:00 LT. This feature is not observed at SJ, where the effect of the EIA is less pronounced.

Venkatesh et al. (2014a) found that at low latitudes and close to the southern crest of EIA, for HSA, $hmF_2$ shows much lower values in winter than during equinox and summer. This feature is observed at both SJ and TU stations. Chuo (2012) studied the characteristics of $NmF_2$, $hmF_2$ and $B_0$ at Chung–Li (24.9°N, 121.1°E; Taiwan), close to the northern crest of EIA, for the HSA year of 1999. It is very interesting to note that $hmF_2$ trends at Chung–Li show a three-peaks behavior for all seasons, with relative maxima occurring at pre-sunrise, local noon, and in the evening hours, with the first two being more pronounced than the third one. Similarly, Batista and Abdu (2004) observed that, for HSA, at Cachoeira Paulista (22.5°S, 45°W; Brazil), close to the southern crest of EIA, $hmF_2$ shows three peaks at sun-rise (around 07:00 LT), pre-noon (around 11:00 LT) and sunset (around 20:00 LT), with the first one visible during all the year and probably caused by the equatorward neutral wind. Bertoni et al. (2006) at SJ also find an $hmF_2$ increase around sunrise for the years 2003–2004. Comparing these results with the trend shown in Fig. 5 for HSA, it is observed that the three-peak behavior is barely visible during equinox and summer at TU, while it is not observed at SJ.

The observed inter-station differences, in particular those observed during equinox for HSA, might be due to a joint action of the longitudinal gradients characterizing the EEJ and the 5.8° separation in dip latitude between the two ionosondes. The analysis of the longitudinal variations of the EEJ has been the focus of a large number of studies (e.g. Rastogi, 1962; Sastri, 1996; Lühr et al., 2004; England et al. 2006; Rastogi et al., 2007, 2013; Alken and Maus, 2007; Shume et al., 2010; Yizengaw et al., 2012, 2014; Alken et al., 2013; Chandrasekhar et al., 2014; Moro et al., 2016; Yamazaki and Maute, 2016; Zhou et al., 2016), that have reported clear differences with longitude, for both long- and short-distance separated sectors. In particular, the EEJ longitudinal variations in the complex South American sector have shown very particular behaviors, as reported by Kane and Trivedi (1982, 1985), Shume et al. (2010), Yizengaw et al. (2014) and Moro et al. (2016). Kane and Trivedi (1982, 1985) compared EEJ measures for two stations located in the South American region, namely Huancayo (12°S, 75°W; Perú) and Eusebio (4°S, 39°W; East Brazil), from October 1978 to September 1979, for quiet geomagnetic conditions, and reported that the electrojet results to be stronger at Huancayo than at Eusebio. Shume et al. (2010) studied the characteristics of the EEJ at Jicamarca (12°S, 77°W; Perú) and São Luís (2.3°S, 44°W; Brazil) during a solar maximum (years 2001–2002) and a solar minimum (years 2006–2007) showing that: (1) the EEJ varies longitudinally, being stronger on the West coast (Jicamarca) than in the East coast (São Luís), for both low and high solar activity conditions; (2) the EEJ has a maximum during equinoxes in Jicamarca, but it has a prominent maximum in solstice season in São Luís; (3) the magnitude of the EEJ is more variable with season and solar cycle in São Luís than in Jicamarca. A similar study has been recently carried out by Moro et al. (2016) who studied the variations of the $E_V$ and $E_Z$ components of the Equatorial Electric Field (EEF) at Jicamarca and São Luís for data collected during the period 2001–2010, under quiet geomagnetic conditions (Kp ≤ 3+). The results revealed that $E_V$ ranges from 0.21 to 0.35 mV/m at São Luís and from 0.23 to 0.45 mV/m at Jicamarca, while the $E_Z$ component ranges from 7.09 mV/m to 8.80 mV/m at São Luís and from 9.00 mV/m to 11.18 mV/m at Jicamarca. Therefore, Moro et al. (2016) show that the EEF varies longitudinally, being the $E_V$ and $E_Z$ components less intense in the Brazilian sector than in the Peruvian one. Finally, using couples of ground-based magnetometers and data from the Ion Velocity Meter (IVM) instrument onboard the Communication/Navigation Outage Forecasting System (C/NOFS) satellite, Yizengaw et al. (2014) studied the behaviors of the EEF and $\mathbf{E} \times \mathbf{B}$ vertical plasma drift, for the period 2009–2013, for five longitudinal sectors: 76.9°W and 69.2°W (West South America), 56.1°W (Center–East South America), 7.6°E (West African coast), 38.8°E (East African coast). The results are very interesting and show that: (1) the EEF, and thus the vertical plasma drift, decreases in magnitude from the American to African sector; (2) the longitudinal EEJ and $\mathbf{E} \times \mathbf{B}$ drift distribution provide higher values in the West American sector and start decreasing moving toward east; (3) the EEJ shows clear seasonal variations with higher magnitudes during equinoxes and lower magnitudes in the June solstice. Further-
more, the study of Yizengaw et al. (2014) shows that, comparing the $\mathbf{E} \times \mathbf{B}$ drift measured at 76.9°W and 56.1°W (only 20.8° separated in longitude in the South American sector), clear differences during March equinox are visible in the range 17:00–21:00 LT. In particular, the impulsive enhancement observed at 76.9°W (peak value of $\sim 30$ m/s around 19:00 LT) is much more pronounced compared to the one observed at 56.1°W (peak value of $\sim 10$ m/s around 18:30 LT). This is a key result that confirms how different relevant differences can be observed also for close longitudinal sectors in the EEJ strength, and consequently in the EIA, in the area of South America under quiet geomagnetic conditions.

By virtue of the aforementioned results, the stronger EIA effect observed at TU station for HSA during March equinox, can be in part attributed to a more pronounced EEJ strength at TU, located 20° West of SJ, which might have led to a more pronounced $\mathbf{E} \times \mathbf{B}$ vertical plasma drift. Indeed, it is important to mention that, as shown in Fig. 1, TU and SJ are located at different geomagnetic field inclination isolines with a 5.8° separation in dip latitude, with isolines at SJ longitudes that are closer than those at TU. These different configurations can considerably affect the geometry of the EIA crest over the 20° of longitudinal range, giving rise to the diverse patterns obtained at SJ and TU, in particular for HSA during equinox. Finally, it is worth noting that the different kind of ionosondes, CADI and AIS-INGV respectively working at SJ and TU, can lead by itself to differences linked to the accuracy of the two instruments. Furthermore, as mentioned, some loss of accuracy could interest the parameter $hmF2$ due to the occurrence of E-valley that can influence the results of the inversion algorithm.

3.2.2. Comparison with IRI-2012 and NeQuick2

Hourly monthly averages of $NmF2$ and $hmF2$ from ionosonde and models are presented in Figs. 6 and 7, respectively. Ionosonde data are shown in black with the corresponding standard deviation as vertical bars. Red and blue lines represent monthly averages from IRI-2012 and NeQuick2 respectively. For both Figs. 6 and 7, the left hand side columns refer to SJ, while right columns refer to TU. Similarly to Figs. 2 and 3, the first row reports equinoctial values, the central row winter values and the bottom row summer values. In Fig. 6, different scales for LSA and HSA are presented to have clear visibility of the electron density variations. The differences between ionosonde values and model outputs are displayed, for every plot, in a bottom side panel. The differences are defined as the IRI-2012 value minus the ionosonde value (in red, $\Delta NmF2_{IRI} = NmF2_{IRI} - NmF2_{Ionosonde}$) and as the NeQuick2 value minus the ionosonde value (in blue, $\Delta NmF2_{NeQuick2} = NmF2_{NeQuick2} - NmF2_{Ionosonde}$). Therefore, a positive/negative difference underlines a model over estimation/underestimation.

A comparison between ionosonde and model values shows that, for both SJ and TU, a good agreement in $NmF2$ predictions is observed in winter for both LSA and HSA. During summer season, the good results obtained in winter are confirmed at SJ for both LSA and HSA and at TU for HSA. Nevertheless, at TU for LSA, both models show an anticipation of two hours in the description of the daily $NmF2$ peak that leads to a daytime overestimation, particularly pronounced in the range 08:00–15:00 LT. During equinox, relevant differences between ionosonde and model values are found. In detail, both models (1) overestimate ionosonde values for LSA during daytime, between 14:00–17:00 LT at SJ and between 08:00–17:00 at TU; (2) for HSA, an underestimation is observed around 22:00–23:00 LT at SJ station; (3) at TU a relevant underestimation occurs for HSA, being particularly pronounced between 14:00–02:00 LT and much more pronounced than that observed at SJ. This last point represents the most striking result because it points out how the modeling of the EIA is far from being well accomplished by both models. It is also worth noting that the model underestimation is larger at TU, where the ionosonde measures a more pronounced EIA than at SJ.

Batista and Abdu (2004) made a comparison between ionosonde measurements and IRI-2001 (using URSI coefficients), considering $foF2$ values recorded at Cachoeira Paulista, for both LSA (from March 1996 to February 1997) and HSA (from March 2000 to February 2001). Only a partial agreement with the results obtained here can be found for HSA, in fact on the one hand it is confirmed the underestimation made by IRI in equinox during nighttime, but on the other hand the overestimation made by both models reported by Batista and Abdu (2004) for winter season around 06:00 LT is not confirmed. De Jesus et al. (2011) made a comparison between IRI-2007 and ionosonde $foF2$ values recorded at SJ, for the year 2003, finding good agreements during all seasons, in particular for the spring months of September and October (equinox). The results we obtain are partially in accordance with those reported by de Jesus et al. (2011), being characterized by differences in particular during equinox for both LSA and HSA. At the northern crest of EIA, Chuo (2012) found significant underestimations made by IRI-2007 between 12:00–22:00 LT during equinox and winter for HSA. This behavior is partially observed during equinox at TU. Ezquer et al. (2014) made a comparison between $foF2$ from ionosonde and IRI-2012 outputs for the very low solar activity years of the last minimum 2008–2009 at TU. They found an evident overestimation given by the model from 08:00 LT to 15:00 LT in summer, which is in agreement with the results reported in this study.

A comparison between $hmF2$ ionosonde data and model outputs, shown in Fig. 7, evidences that, according to Batista and Abdu (2004), the models work better for LSA than for HSA, both at SJ and TU. Focusing on the results for SJ, the models underestimate the uplift observed during daytime hours for HSA. This feature is visible for all seasons and particularly pronounced in summer between 09:00–18:00 LT. These results are in accordance
with those of de Jesus et al. (2011), who compared the ionosonde measured \( h'F2 \) values with IRI-2001 and IRI-2007 \( hmF2 \) outputs at SJ for the high solar activity year 2003, and reported a particularly pronounced underestimation made by both versions of IRI during daytime hours in summer. For LSA at SJ, the models provide a good agreement with ionosonde data for both equinox and winter. In summer, it is observed an underestimation made by both models between 11:00–17:00 LT. At TU, both models provide very good performances, in particular during winter season (for both LSA and HSA). Nevertheless, at TU both models provide underestimations in some particular cases. As previously pointed out, at TU for HSA in equinoctial season, an impulsive \( hmF2 \) increase/decrease is observed between 17:00 LT and 00:00 LT. Both models do not follow this enhancement, providing underestimations between 19:00–21:00 LT.

Table 2 summarizes the differences between ionosonde values and model outputs for \( NmF2 \), \( hmF2 \), \( B_0 \) and \( B_1 \). The model reliability is emphasized through a point-to-point relative percentage “distance” defined as \( |A_{\text{Model}} - A_{\text{Ionosonde}}| / A_{\text{Ionosonde}} \times 100 \), with \( A \) representing one of the four aforementioned parameters. The table reports LSA, HSA and ‘Overall’ percentage average distances, obtained averaging over the 24 h and over September, June and December 2008 for LSA, over March 2014, July/August 2014 and December 2013 for HSA, and over all the six months for the ‘Overall’ value. Of course, a good model reliability is indicated by a low percentage value.

Comparing the results given by models for the peak electron density, slightly better estimations are made by IRI-2012 than NeQuick2, for both SJ and TU. Moreover, average overall percentages of 33% (IRI) and 56% (NeQuick2) have been obtained for SJ, and 42% (IRI) and 58%
In general, our results for the peak parameters suggest that the IRI-2012 description of the bottom side profile (Eqs. (1) and (2)) appears more accurate than the NeQuick2 one (Eqs. (3) and (4)), with the peak electron density $NmF2$ representation that needs to be improved in NeQuick2. Differences between IRI-2012 and NeQuick2 in terms of $hmF2$ are not particularly relevant, the models

Table 2 Relative percentage average distances between ionosonde and model values. The single percentage distance is calculated as \(\left(\frac{|A_{\text{Model}} - A_{\text{ionosonde}}|}{A_{\text{ionosonde}}}\right) \times 100\), where $A$ can be one of the parameters $NmF2$, $hmF2$, $B_0$ and $B_1$. LSA (or HSA) averages have been obtained averaging over the 24 h and over the three considered months (September, June and December 2008 for LSA; March 2014, July/August 2014 and December 2013 for HSA). Overall averages have been calculated in the same manner but averaging over all the six considered months.

<table>
<thead>
<tr>
<th>Station</th>
<th>Parameter/Model</th>
<th>IRI–2012</th>
<th>NeQuick2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LSA</td>
<td>HSA</td>
<td>Overall</td>
</tr>
<tr>
<td></td>
<td>LSA</td>
<td>HSA</td>
<td>Overall</td>
</tr>
<tr>
<td>São José dos Campos</td>
<td>$NmF2$</td>
<td>29%</td>
<td>37%</td>
</tr>
<tr>
<td></td>
<td>$hmF2$</td>
<td>11%</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td>$B_0$</td>
<td>17%</td>
<td>21%</td>
</tr>
<tr>
<td></td>
<td>$B_1$</td>
<td>33%</td>
<td>23%</td>
</tr>
<tr>
<td>Tucumán</td>
<td>$NmF2$</td>
<td>44%</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>$hmF2$</td>
<td>7%</td>
<td>13%</td>
</tr>
<tr>
<td></td>
<td>$B_0$</td>
<td>17%</td>
<td>18%</td>
</tr>
<tr>
<td></td>
<td>$B_1$</td>
<td>44%</td>
<td>20%</td>
</tr>
</tbody>
</table>

(NeQuick2) for TU, confirming the better performances obtained at SJ by using IRI. For the parameter $hmF2$, Table 2 points out that: (1) NeQuick2 works slightly better than IRI for both stations and for both LSA and HSA; (2) better agreements are obtained for LSA than for HSA; (3) contrary to what obtained for $NmF2$, better performances have been obtained at TU.

Fig. 7. Same as Fig. 6 for $hmF2$. In this case the unit of the y axis is the same for all panels.
provide similar results. However, further comparisons at both low- and mid-latitude sites are recommended in order to have an improved knowledge of the F2-layer peak parameters description made by the two models.

3.3. Bottom side thickness \((B_0)\) and shape \((B_1)\) parameters

The comparison of average diurnal variations of the bottom side profile thickness and shape parameters, \(B_0\) and \(B_1\), are reported in Fig. 8 and Fig. 9 respectively. Both figures are structured in the same way of Figs. 5 and 6, with results for SJ on the left and for TU on the right. Values for equinox (first row), winter (second row) and summer (third row), for LSA (left column) and HSA (right column), are displayed for every station. A bottom side panel displays the measured differences between ionosonde and model values for every plot.

It is seen from Fig. 8 that \(B_0\) daily variations derived from ionosonde show a similar pattern at SJ and TU. A pre-noon maximum around 10:00 LT is observed during equinox and summer, both for LSA and HSA. The noon-time maximum of \(B_0\) is attributed to the upward plasma flow at the equator (Chuo, 2012), and appears more pronounced in summer. A flattened trend characterizes the winter season for HSA at SJ and for both LSA and HSA at TU. Sethi et al. (2009) compared the parameters \(B_0\) and \(B_1\) measured at New Delhi (28.6°N, 77.2°E; India) with the outputs of IRI-2007 for LSA (January 2004–August 2006). They found a clear increase (20% to 80%) of the measured \(B_0\) from LSA to HSA during winter and equinox, while in summer the increase was within 30%. In the present study, a tendency to increase is observed during equinox and summer at TU, while at SJ, the \(B_0\) values increase from LSA to HSA only during nighttime hours with a reverse pattern during daytime. Moreover, accordingly with Sethi et al. (2009), a slight dependence of \(B_0\) values on season is observed, with higher values in summer and lower in winter.
Interesting analyses about a possible correlation between $B_0$ and $hmF2$ variations have been carried out by Sethi et al. (2007), Chuo (2012) and Zhang et al. (2008). Sethi et al. (2007) made a comparison between bottom side profile parameters recorded by the ionosonde of New Delhi and IRI-2001 for the HSA years 2001–2002. They found a good correlation (linear correlation coefficient of 0.7) between $hmF2$ and $B_0$ in winter and equinox during daytime hours (06:00–18:00 LT). Chuo (2012) also found a correspondence between $hmF2$ and $B_0$ for all seasons at the northern crest of the EIA. Zhang et al. (2008) found a strong positive linear correlation between $hmF2$ and $B_0$ during daytime hours at Hainan station (19.4°N, 109.0°E; China) for mid/high solar activity. The importance of this analysis can be found in the implications that a high correlation between $hmF2$ and $B_0$ can have, providing the possibility to obtain synthetic $B_0$ values directly from $hmF2$, which is easier to obtain from experimental data (Zhang et al., 2008).

The $B_0$ pattern observed for HSA is in good agreement with the results of Chuo (2012) and a correlation can be perceived between $hmF2$ and $B_0$ at SJ and TU for both LSA and HSA. Nevertheless, unlike those reported by Sethi et al. (2007), between 06:00–18:00 LT, the present study reveals a good linear correlation at SJ for all seasons during HSA (0.87 at equinox, 0.57 in winter and 0.51 in summer), while at TU good linear correlations are found for HSA during equinox (0.69) and summer (0.85). Fig. 10 shows the linear correlation between $B_0$ and $hmF2$ for both stations, for all seasons during HSA, between 06:00–18:00 LT. The possible reason behind the relationship between $hmF2$ and $B_0$ could be find in a “cross-action” of equatorward neutral winds and EIA. Southward/equatorward neutral winds can induce an upward plasma drift and, under the action of the upward velocity, a simultaneous F-layer uplift (increasing of $hmF2$) and $B_0$ increase can occur. Fejer et al. (1995), studying the global plasma drift during daytime hours at equato-
arial latitudes, found that an upward plasma flow can occur during 06:00–09:00 LT in equinox and summer, with a longer duration (until 13:00 LT) in winter. This result can explain the $B_0$ pattern observed by Chuo (2012) during 06:00–13:00 LT, indicating that the vertical plasma drifts can play an important role concerning the $B_0$ features in the EIA region. On the other hand, the EIA and in particular the EEJ should be taken into account. Obrou et al. (2003) found that both $hmF2$ and $B_0$ have a strong linear positive correlation with the EEJ strength around midday hours in the equatorial West African sector. This result confirms what was found by Abdu et al. (1990) in the South American sector, proving how the electric field $E$ that drives the EEJ plays a major role in the variations of both the thickness parameter $B_0$ and the peak electron density height $hmF2$. However, further studies about the relationship between $hmF2$ and $B_0$, in particular for low-latitude ionosondes, are necessary to have a clear description of the phenomenon and its driving physical mechanisms.

A comparison of experimental $B_0$ with the outputs of IRI-2012 and NeQuick2 shows that, for both stations, a good agreement with IRI is obtained, in particular during equinox. In winter, an IRI overestimation is visible for HSA during daytime hours (09:00–17:00 LT) at both stations, with NeQuick2 that provides better agreements than IRI. These results are in accord with those reported by Venkatesh and Fagundes (2016), while they differ from the ones reported by Sethi et al. (2007) and Chuo (2012) who compared ionosonde values with both $B_0$ “standard” option and Gulyaeva method (Gulyaeva, 1987) for the bottom side profile given as output by the IRI model. In summer, weak correspondences with models are found. At SJ, both models underestimate the ionosonde values around the daily peak for LSA; for HSA, NeQuick2 provides better agreements with ionosonde data than IRI which significantly overestimate observed values between 11:00–17:00 LT. For the same season at TU, both models strongly underestimate the daily peak for HSA occurring at around 10:00 LT, while better correspondences are obtained during nighttime hours. Using data from Cachoeira Paulista, Batista and Abdu (2004) found that the IRI amplitude of the $B_0$ daily variation is much smaller than those estimated from observations, with larger discrepancies during summer months of HSA, which results in a tendency to underestimate the daily maximum around midday or overestimate the nighttime values. Our results confirm this pattern at both stations only in summer for LSA. For HSA the maximum daily peak is described very well at SJ and just slightly underestimated at TU. In accord with Sethi et al. (2007), good results are obtained during nighttime hours.

In general, the qualitative values provided by the NeQuick2 model underestimate the ionosonde values at
SJ and TU for LSA, while better correspondences than IRI can be found at SJ for HSA. Instead, at TU the IRI model provides very good results for LSA and for HSA during equinox and summer months, respectively. The overall percentage average distances between ionosonde and modeled values reported in Table 2 reveal that IRI and NeQuick2 provide the same results (~19%) at SJ, while at TU IRI provides better results than NeQuick2. However, it is interesting to observe that IRI provides better results for LSA than for HSA, while the contrary is observed for the NeQuick2 model.

The diurnal variations of the shape parameter $B_1$ are displayed in Fig. 9. Comparing the values of $B_1$ obtained from ionosonde profiles recorded at SJ and TU, significant inter-station differences are obtained for HSA, while trends are quite similar for LSA. In detail, at SJ, $B_1$ values show small differences between nighttime and daytime values in equinox and winter for HSA; in summer, a decrease between 09:00–12:00 LT modifies the flat trend observed for the remaining hours of the day. At TU the results are different and show a similar pattern for all seasons characterized by high values of $B_1$ (between 3 and 4) during nighttime hours, with a decrease and consequent low values (between 1 and 2) during daytime hours (08:00–17:00 LT).

In contrast to the results of Sethi et al. (2007, 2009), the comparison between measured values and IRI-2012 and NeQuick2 outputs shows that both models do not catch correctly the observed ionosonde trends of $B_1$. The qualitative values of $B_1$ obtained by fitting NeQuick2 profiles with Eq. (1) generally underestimate the ionosonde values, in particular at SJ during HSA where differences larger than 2 can be reached during nighttime hours. Concerning IRI-2012, good correspondences with ionosonde values are obtained only in winter for HSA at TU. On the contrary, the most relevant differences between ionosonde values and IRI outputs are registered: (1) during equinox and winter seasons for LSA at both stations, where IRI provides relevant overestimations; (2) for HSA in summer, where a clear underestimation is observed during all day at SJ and between 19:00–07:00 LT at TU.

As shown in Table 2, the overall percentage distances for the parameter $B_1$, 28% (IRI) and 40% (NeQuick2) at SJ, and 32% (IRI) and 34% (NeQuick2) at TU, reveal how IRI-2012 provides better results than NeQuick2 for $B_1$. However, despite the qualitative $B_1$ values provided by NeQuick2, it is interesting to underline that, during daytime hours of LSA at TU and during all day of LSA in winter season for both SJ and TU, correspondences between NeQuick2 and ionosonde values are better than those observed for IRI.

4. Conclusions

Bottom side electron density profiles at two closely separated stations (at similar latitude and 20° separated in longitude) located at the southern crest of the EIA in the South American sector, namely São José dos Campos (23.1°S, 314.5°E, dip latitude 19.8°S; Brazil) and Tucumán (26.9°S, 294.6°E, dip latitude 14.0°S; Argentina), have been compared among them and with the outputs of the IRI-2012 and NeQuick2 models. The analysis was carried out selecting a representative month for equinoctial, winter and summer seasons during the very low solar activity year 2008 (sunspot annual average $R = 3$) and the high solar activity years 2013–2014 ($R = 65$ and $R = 113$ respectively), under quiet geomagnetic conditions.

A careful investigation of the diurnal and seasonal variations of the F-layer peak parameters $NmF2$ and $hmF2$ at both sites reveals corresponding higher values for HSA than for LSA. Concerning $NmF2$, results show that: (1) the EIA is at its maximum strength during equinox season for HSA; (2) pronounced inter-station differences are found during this period, with the EIA effect that is more pronounced at TU than at SJ. Furthermore, at TU the nighttime high values of $NmF2$ (peak around 21:00 LT) during equinox for HSA are linked to an impulsive contemporary increase of $hmF2$, showing a kind of “elastic rebound” of the ionosphere.

The significant inter-station difference found in the EIA effect suggests that relevant longitudinal-dependent variations in the EIA can occur. These differences can be properly explained considering that: (1) the EEJ in the South American sector is characterized by a significant longitudinal gradient, with pronounced variations also for very close longitudinal sectors; (2) concerning the dip latitude, there is a difference of 5.8° between the two ionosondes, which are consequently characterized by different geomagnetic field configurations. It is important to underline that relevant differences in the EIA effect are found under quiet geomagnetic conditions for two so close ground-based ionosondes in South America for the first time. Therefore, further studies in this sector on ionospheric characteristics recorded at close longitude locations nearby the southern crest of the EIA gain significant importance.

IRI-2012 and NeQuick2 bottom side electron density profiles show significant deviations from the ionosonde observations. The best agreements are found around sunrise (07 LT), with larger differences around noon (13 LT) and sunset (19 LT). A better correspondence has been observed at SJ than at TU, and better results are obtained for LSA than for HSA. In general, the IRI-2012 model shows better agreements with the observations than the NeQuick2 model. Nevertheless, NeQuick2 provides better results in the height range around 250 km at 13 LT, the region at which both models overestimate the ionosonde electron density.

Concerning the comparison between ionosonde and models for $NmF2$, relevant differences are observed during equinox when the following pattern is observed for both stations: (1) for LSA both models overestimate daytime values; (2) for HSA both models tend to underestimate nighttime values, with very pronounced differences at TU. Therefore, large discrepancies between ionosonde values and model outputs are observed when the EIA is at its
maximum strength. Moreover, the IRI-2012 model provides more reliable results than NeQuick2 for both stations, with better correspondences with ionosonde data for LSA than for HSA. The $hmF2$ parameter is described quite well for LSA. For HSA larger differences with model predictions have been observed in particular at SJ, where both models underestimate the uplift observed during daytime hours. Moreover, both models do not follow the impulsive increase of $hmF2$ observed at TU for HSA during equinox around post-sunset hours, providing consequently a clear underestimation. Accordingly to the results obtained for $NmF2$, both models provide better results for LSA, but in this case, the NeQuick2 model provides more reliable results than IRI for both stations.

SJ and TU show a similar diurnal pattern for the parameter $B_0$: (1) a pre-noon peak value around 10:00 LT observed during equinox and summer, for both LSA and HSA; (2) a peak around noon that is more pronounced in summer; (3) a moderate seasonal dependence with $HSA$.

Differences in model performances have to be ascribed to the corresponding different description used to model the bottom-side electron density profile. In general, the IRI-2012 description, for ionosondes located around the south crest of the EIA in the South American sector, appears more appropriate than the semi-Epstein layer description used by NeQuick2.

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References


