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*Nm*F2 trends at low and mid latitudes for the recent solar minima and comparison with IRI-2012 model

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Abstract

The ionospheric electron density peak (*Nm*F2) is analyzed for the recent minima of solar activity for two mid-latitude stations, Rome (41.8°N, 12.5°E, geomagnetic latitude 41.7°N, Italy) and Gibilmanna (37.9°N, 14.0°E, geomagnetic latitude 37.6°N, Italy), and for the low-latitude station of Tucumán (26.9°S, 294.6°E, geomagnetic latitude 17.2°S, Argentina), located in the south ridge of the equatorial ionization anomaly. An inter-minima comparison reveals that from an ionospheric point of view the last minimum of solar activity (minimum 23/24) was peculiar, with values of *Nm*F2 lower than those recorded during the previous minima for all the stations and all the hours of the day. A more pronounced decrease is observed at Tucumán than at Rome and Gibilmanna. The study of the winter and semi-annual anomaly shows that at mid-latitude stations the winter anomaly is not visible only for the years 2008 and 2009, which represent the deeper part of the prolonged and anomalous last solar minimum. The same is for the semi-annual anomaly. A comparison with the version 2012 of the International Reference Ionosphere model (IRI) is also carried out. The results reveal that for low solar activity the model works better at mid latitudes than at low latitudes, confirming the problems of IRI in correctly representing the low-latitude ionosphere. Nevertheless, using as input updated values of the solar and geomagnetic indices, no loss of accuracy is detected in the IRI performances for the last solar minimum with respect to the previous ones, both at mid and low latitudes.

Keywords: Ionosphere; Ionospheric electron density peak; IRI model; Solar minimum; Solar cycle

1. Introduction

The ionosphere is produced by the ionization of the neutral atmosphere caused by the solar radiation and it is then expected to follow the Sun's behavior (e.g., Araujo-Pradere et al., 2011; Hargreaves, 1992; Liu et al., 2006, 2011; Solomon et al., 2010, 2013). The solar Extreme Ultra Violet irradiance (10–120 nm) represents the main ionization source of the ionospheric F2 layer (e.g., Chen et al., 2012; Tobiska, 1996), and significantly affects the variability of ionospheric parameters such as the critical frequency of the F2 layer (*fo*F2), and the corresponding maximum of electron density (*Nm*F2) and height (*hm*F2).

The time variation of *Nm*F2 is expected to follow almost identically the variations of the solar activity, owing to the

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main control that the activity of the Sun has on the ionosphere. In particular, there is an increasing interest in the study of the ionospheric plasma response to extreme solar activity conditions, that is for periods of maximum or minimum solar activity.

The last solar minimum, between solar cycles 23 and 24 (minimum 23/24), offers a unique natural window to study the ionosphere under very particular conditions of solar activity. The minimum showed very interesting and unprecedented characteristics. In particular, 527 spotless days were recorded for the two years 2008 and 2009, while for the minima 22/23 (years 1996–1997) and 21/22 (years 1986–1987) were respectively 226 and 176; moreover, 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 of the solar–wind pressure since the mid-1990s, the lowest point since the start of such measurements in the 1960s (Phillips, 2009). On the other hand, the Whole Heliosphere Interval (WHI), an internationally coordinated observing and modeling effort, reported that WHI solar–wind speed and radiation–belt flux were high compared to prior minima (Gibson et al., 2009).

Emmert et al. (2010) found that during the period 2007–2009 thermospheric densities at a fiducial altitude of 400 km have been the lowest ever observed over the last 43 years. Gentile et al. (2011) using measurements by the Defense Meteorological Satellite Program studied the occurrence of Equatorial Plasma Bubbles (EPB), and for solar maximum years they found many orbits showing the presence of EPB, the number of which decreased to about 10% for the minimum 22/23, and to less than 5% for the minimum 23/24. Chen et al. (2011) showed that the decrease of the solar EUV irradiance from the minimum 22/23 to the minimum 23/24 was much larger (15%) than the decrease of $F_{10.7}$ (5%), highlighting that this widely used index is not a good indicator of EUV variations for the last solar minimum.

Strictly linked to the solar activity level, two typical ionospheric anomalies can be analyzed to detect the anomalous conditions characterizing the last solar minimum: the *winter anomaly* and the *semi-annual anomaly* (Chen and Liu, 2010; Dominici, 1971; Ezquer et al., 2014; Liu et al., 2012; Rishbeth and Setty, 1961; Rishbeth and Garriot, 1969; Rishbeth et al., 2000; Torr and Torr, 1973; Yonezawa and Arima, 1959; Yonezawa, 1967, 1971).

The winter anomaly consists of the observation of local noon *Nm*F2 values lower in summer than in winter. It has been proposed that this anomaly is related to changes in the neutral composition of the atmosphere, generated by a heating of the summer hemisphere which gives rise to a convection of lighter neutral elements toward the winter sector, which causes changes in the ratio of $[O]/[N_2]$ in both hemispheres (Johnson, 1964; Rishbeth and Setty, 1961; Torr and Torr, 1973). This anomaly, which is significantly affected by the solar activity, tends to disappear for low solar activity at low latitude (e.g., Ezquer et al., 2014). The semi-annual anomaly is characterized by values of *Nm*F2 that are greater around equinoxes (April and October) than solstices (June and December). This anomaly is more visible at low latitudes (e.g., Ezquer et al., 2014; Rishbeth and Garriot, 1969), and the corresponding amplitude is larger for high solar activity (Ma et al., 2003). Several mechanisms have been proposed to explain this anomaly. Yonezawa (1971) proposed that it is related with the variation of the upper atmosphere temperature. Torr and Torr (1973) suggested that this is due to semi-annual variations in neutral densities associated with the geomagnetic and auroral activity. Mayr and Mahajan (1971) showed that the anomaly requires significant variation in the neutral composition at lower height. Ma et al. (2003) suggested that the semi-annual variation of the diurnal tide in the lower thermosphere induces the semi-annual variation of the amplitude of the equatorial electrojet, thus causing the semi-annual anomaly at low latitude.

Anyhow, the winter anomaly and the semi-annual anomaly depend on the solar activity and therefore they represent good indicators to assess the influence of the very low solar activity of the last minimum.

In addition to the aforementioned particularities, the last solar minimum was also characterized by a very long duration. In fact, the last minimum began around March 2006 and many predictions of the start and size of solar cycle 24 were given thereafter (Pesnell, 2008). In 2007, the solar cycle 24 Prediction Panel anticipated that the solar minimum marking the onset of cycle 24 would occur in March 2008 ($\pm$6 months). This date was then corrected to August 2008. In the next update, users were informed that the solar minimum would occur in December 2008 (http://www.swpc.noaa.gov/SolarCycle/SC24/index.html). The minimum actually happened in the middle of 2009 and thus more than 2 years after the earliest prediction (Zakharenkova et al., 2013).

The problem linked with the predictability of this minimum can be well fixed looking at Fig. 1 where monthly median values for three different updates of the Ionospheric Index IG12 (Liu et al., 1983) are plotted for the recent solar cycles. The black curve identifies values of the IG12 index updated on 27 November 2006, this meaning that values plotted after this date are forecasted values. The red and blue curves represent the update made on 16 January 2013 and 20 February 2015 respectively. With a focus on the deeper part of the last minimum (2008–2009), it is then possible to note that this minimum was expected well before and with a level of solar activity higher than the measured one.

The International Reference Ionosphere (IRI) (e.g. Bilitza et al., 1990; Bilitza, 2001; Bilitza and Reinisch, 2008; Bilitza et al., 2014) is the best-known and most widely used 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

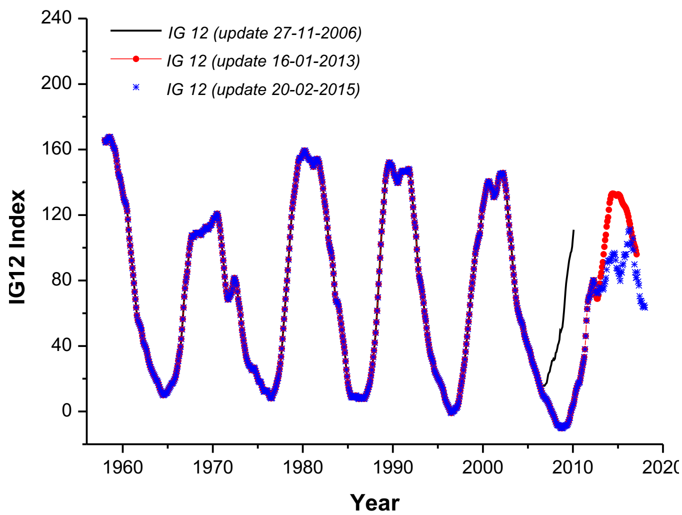

Fig. 1. Monthly median values of the Ionospheric Index IG12 for the recent solar cycles. Three different updates are displayed: update on 27 November 2006 (black line), update on 16 January 2013 (red dots) and update on 20 February 2015 (blue asterisks). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

characteristics of the ionosphere for quiet and storm-time periods, such as the electron density, the electron content, the electron temperature and the ion composition, as a function of height, location, and local time (e.g. Araujo-Pradere et al., 2011, 2013; Zakharenkova et al., 2013). IRI results depend on several input parameters, like the solar activity and magnetic indices, and the use of uncertain predicted values of them can lead to significant discrepancies in the model outcome (Zakharenkova et al., 2013). The IG12 index shown in Fig. 1 represents one of the parameters used as input by the model (but the same is for the solar index $F_{10.7}$), and it was therefore expected that IRI had some problems in representing the ionosphere during the minimum 23/24, also because there were no previous data recorded under similar conditions for IRI modeling (Bilitza et al., 2012).

In this study, an analysis of the minimum 23/24 is carried out using *Nm*F2 values recorded by three ionospheric stations, specifically two mid-latitude stations in Italy, and a low-latitude station in Argentina. The main aims of the work are: (1) to make an inter-minima comparison, in order to catch the particularity of the last minimum and to look for possible latitude dependences; (2) to compare the measurements made at the three stations with the output given by the IRI-2012 (hereafter IRI) model.

The datasets used and the analysis method are described in Sections 2 and 3. The results and discussion are the subject of Section 4, while Section 5 reports the conclusions.

2. Data sources

*Nm*F2 represents the maximum electron density of the ionospheric vertical electron density profile. It is linked to *fo*F2, which indicates the maximum frequency that can be reflected by the ionosphere for an electromagnetic wave traveling vertically, by the relation:

$$NmF2[\mathrm{m}^{-3}] = 1.24 \cdot 10^{10} (foF2[\mathrm{MHz}])^2 \quad (1)$$

Values of *Nm*F2 were calculated using Eq. (1), starting from manually validated values of *fo*F2. *fo*F2 values were validated according to the International Union of Radio Science (URSI) standard (Wakai et al., 1987), and all the corresponding numerical values were considered independently of the presence of qualifying and descriptive letters. *fo*F2 validated data were downloaded from the electronic Space Weather upper atmosphere database (eSWua; http://www.eswua.ingv.it/) (Romano et al., 2008).

In this study we considered *fo*F2 data recorded at three stations: Rome (41.8°N, 12.5°E, geomagnetic latitude 41.7°N) and Gibilmanna (37.9°N, 14.0°E, geomagnetic latitude 37.6°N), Italy, and Tucumán (26.9°S, 294.6°E, geomagnetic latitude 17.2°S), Argentina.

At Rome station, *fo*F2 values were all validated from traces recorded by classical ionosondes, which cannot tag the different polarization characterizing the two different modes of propagation of the electromagnetic wave. A VOS–1 chirp ionosonde produced by the Barry Research Corporation, Palo Alto, CA, USA (Barry Research Corporation, 1975) sounded from January 1976 to November 2004, and then it was replaced by an AIS-INGV ionosonde (Zuccheretti et al., 2003). Therefore, a very long and continuous dataset is available, with hourly validated values of *fo*F2 starting from January 1976, and monthly median values of *fo*F2 starting from 1957: a period covering the last five solar cycles.

The Gibilmanna station is equipped with an AIS-INGV ionosonde since November 2002. Before, the ionospheric observatory was equipped with a Digisonde 128P produced by the Center for Atmospheric Research of the University of Lowell, MA (USA) (Bibl and Reinisch, 1975). The ionograms were recorded on paper and manually scaled by specialized operators. For this station, data are available starting from April 1976, but unfortunately the dataset is discontinuous with a lack of data for many years. For our purposes, the minimum 21/22 (1986–1987) and 23/24 (2008–2009) will be representative for this station.

The ionospheric measurements at Tucumán began in 1957, the International Geophysical Year, when an analogical ionosonde was transferred from the Navy of Argentina to the National University of Tucumán. That ionosonde stopped working in 1987 (Ezquer et al., 2014). In August 2007, an AIS-INGV was installed at the Upper Atmosphere and Radiopropagation Research Center of the Regional Faculty of Tucumán of the National Technological University (UTN). Data for the last five minima, except for the minimum 22/23, are available for this station.

Table 1 reports the solar minima for which *Nm*F2 values are available for the three stations. It is important to

Table 1
Solar minima for which $NmF2$ values are available for Rome, Gibilmanna and Tucumán stations.

Station	Solar minima for which $NmF2$ values are available
Rome	19/20 – 20/21 – 21/22 – 22/23 – 23/24
Gibilmanna	21/22 – 23/24
Tucumán	19/20 – 20/21 – 21/22 – 23/24

underline that in every case and for all the stations considered, the values of $foF2$ used to calculate $NmF2$ have been manually validated. Therefore, the time series considered in this study represent a reliable and homogeneous datasets.

Values of $NmF2$ from the IRI model were obtained using as input the latest updates for the solar and geomagnetic activity indices. In particular, owing to the fact that the IRI model uses the ionospheric-effective solar index IG12 to obtain $NmF2$ (Bilitza et al., 2012), it is important to underline that the latest available IG12 update was used. Furthermore, after a preliminary comparison for the Rome station, the International Radio Consultative Committee (CCIR) coefficients (1967a, 1967b) were preferred to the Union of Radio Science (URSI) (Rush et al., 1989) ones. This result is expected because the CCIR coefficients are recommended for locations on the continents, whereas URSI coefficients are recommended for the ocean areas (Rush et al., 1989).

3. Analysis method

The analysis carried out for this work can be divided in two main parts: (1) an inter-minima comparison of $NmF2$; (2) a comparison between measured $NmF2$ values and those given as output by the IRI model. For each considered minimum of solar activity, two years were chosen as representative using the following scheme: 1964–1965 (min 19/20), 1975–1976 (min 20/21), 1986–1987 (min 21/22), 1996–1997 (min 22/23), and 2008–2009 (min 23/24).

To obtain a quantitative and reliable minimum-to-minimum difference, only the continuous hourly validated data available for the three stations have been used. Therefore, this analysis takes into account only the last three solar minima: the minimum 21/22 (years 1986–1987), the minimum 22/23 (years 1996–1997) and the minimum 23/24 (years 2008–2009). From hourly validated data, seasonal median values were calculated in the following way: for each considered year, four seasons were definite considering 60 days around the March Equinox (Days of the Year (DOY) from 51 to 111), around the June Solstice (DOY 144–204), around the September Equinox (DOY 237–297), and around the December Solstice (DOY 327–022). For every season and every minimum, the hourly representative value is then calculated as a median of 120 values (60 values for every year). It is worth highlighting that the median is calculated only if at least 40 values out of 120 are available. With these choices, the comparison between different minima can be considered highly reliable, as already shown by Liu et al. (2012). It is important to underline that data from the last three solar minima are available only for the Rome station. For Gibilmanna and Tucumán stations, only a comparison between the last minimum and the minimum 21/22 is possible. Figs. 2 and 3 show the results for Rome and Tucumán, the results for Gibilmanna (not shown here) are very similar to those of Rome.

Monthly median values of $NmF2$ will be instead used to analyze the winter and the semi-annual anomalies. In particular, hourly median values for April and October (equinox) and June and December (solstice) were considered. Monthly median values are available for Rome for the last five minima; for Tucumán, data of the minimum 22/23 are not available, while for Gibilmanna data are available only for minima 21/22 and 23/24. The monthly median values have been calculated only if at least 15 values were available for a month. Figs. 4 and 5 show the results for Rome and Tucumán.

The comparison between observed values and IRI outputs is done by considering hourly monthly median values for the two years included in each minimum. The considered data are those used for the study of the winter and semi-annual anomalies. Fig. 6 shows a preliminary result that is very useful to understand the effect that the particular last minimum had on the ionospheric model outputs. The figure shows the observed hourly monthly median values of $NmF2$ for the years 2008 and 2009 compared with those given as output by IRI by considering values of the IG12 index updated respectively on 20/02/2015 and on 27/11/2006, for Rome station. The IG12 values are the same displayed in Fig. 1. It is clear that using forecasted values of IG12, huge overestimations (more than 100% in some cases) made by the IRI model are observed for 2008 and 2009. The overestimation is more pronounced for the 2009 because the forecasted values of IG12 were calculated for this year by imaging the start of the increasing phase of cycle 24, while the observed values have shown that during the 2009 the minimum 23/24 was still in a deep phase. For the analyses carried out to compare $NmF2$ values obtained from ionosonde and IRI, observed values of IG12 and all others solar/geomagnetic indices were used as input for IRI. Moreover, after a preliminary phase of test, CCIR coefficients have been preferred to the URSI ones.

To catch the performances of IRI, the relative percentage difference ($PD(\%)$ parameter) was calculated according to Bilitza et al. (2012):

$$PD(\%) = \frac{(NmF2_{IRI} - NmF2_{Iono})}{NmF2_{Iono}} \cdot 100, \quad (2)$$

where $NmF2_{IRI}$ and $NmF2_{Iono}$ are respectively monthly median values calculated by using IRI outputs and ionosonde data.

To display the results, opportune percentage relative difference maps were created (Fig. 7). In these maps, the $PD(\%)$ parameter is plotted with the local time on the x axis and the month on the y axis. Therefore, using a

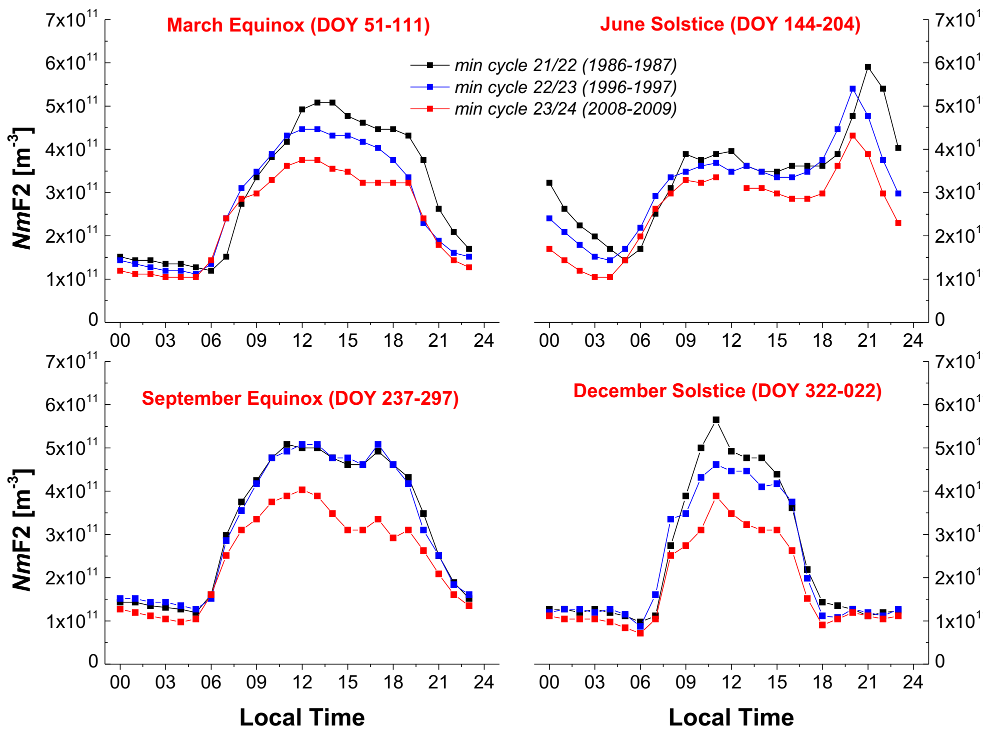

Fig. 2. Seasonal median values of *Nm*F2 for the minimum 21/22 (black squares), 22/23 (blue squares) and 23/24 (red squares), for Rome. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

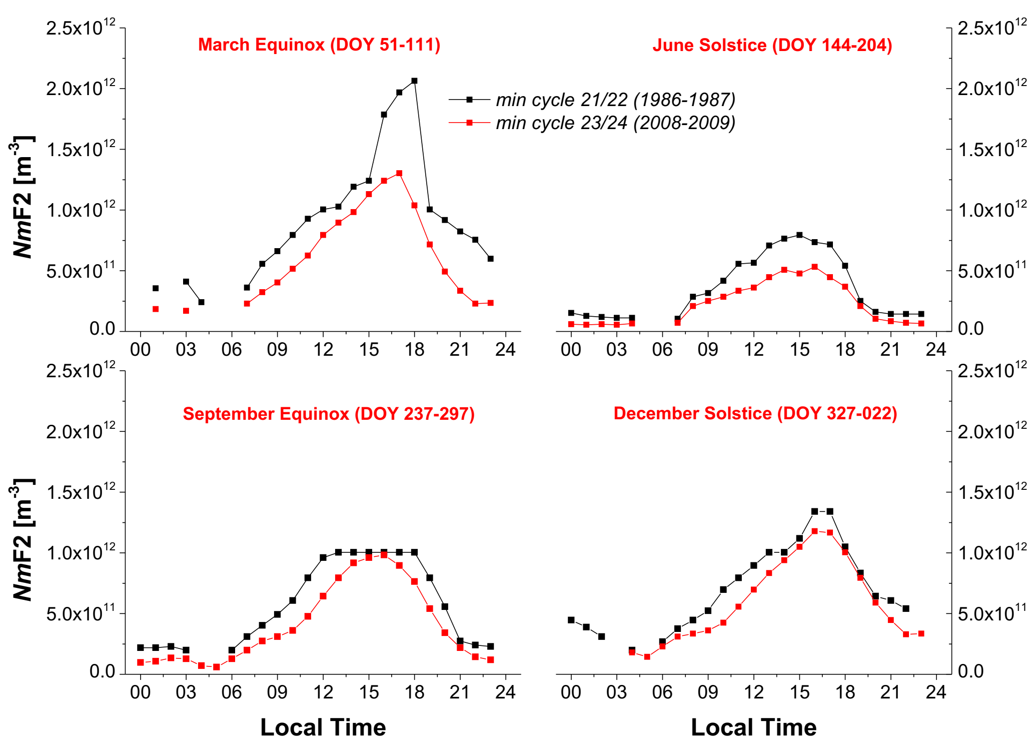

Fig. 3. Same as Fig. 2 but for Tucumán.

chromatic scale, it is possible to visualize easily zones of underestimation/overestimation made by the IRI model. Furthermore, for every map a unique percentage value is calculated, that is a mean of $|PD(\%)|$ on 24-h and two-years values, for each minimum (see Table 2). In this way, we have a measure of the "distance" between observed values and IRI model predictions. Comparing this value for different minima and for different latitudes,

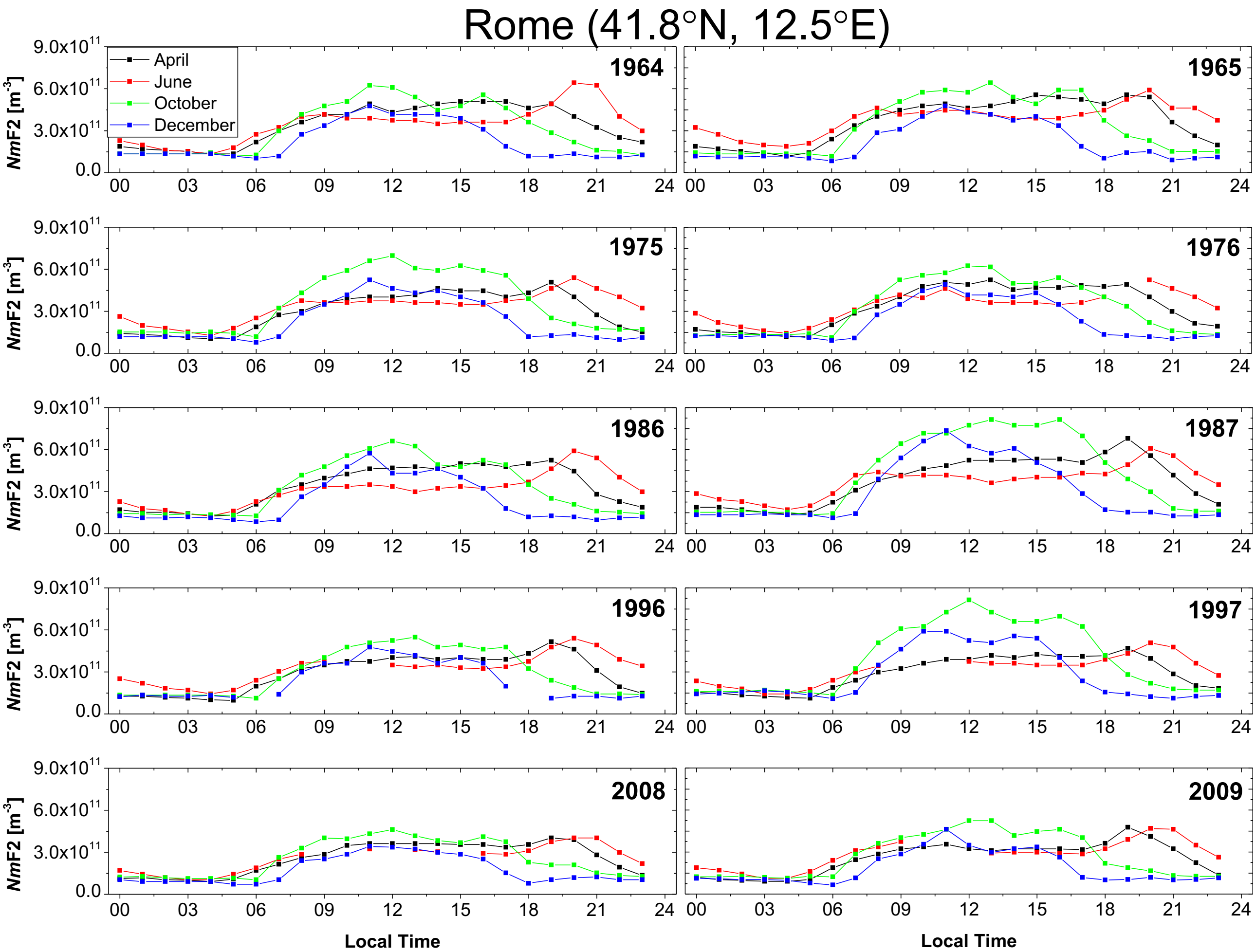

Fig. 4. Hourly monthly median values for April (black squares), June (red squares), October (green squares) and December (blue squares), for the solar activity minimum 19/20, 20/21, 21/22, 22/23, and 23/24, for Rome. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

we can evaluate if there have been a real worsening of IRI performances for the last minimum and if latitudinal dependences of IRI are observed. A possible dependence on the hours of the day is analyzed by plotting the parameter *PD*(%) for each available minimum, for daytime hours (10–14 LT) and nighttime hours (22–02 LT), as it is shown in Fig. 8.

4. Results and discussion

4.1. Inter-minima comparison at mid and low latitudes

Figs. 2 and 3 show the inter-minima comparison of *Nm*F2 for the mid-latitude station of Rome and the low-latitude station of Tucumán, by considering the minimum of cycle 21/22 (black points), the minimum of cycle 22/23 (blue points), and the minimum of cycle 23/24 (red points).

It is possible to observe that the values measured for the last solar minimum are lower than those of previous minima. This is true for all the stations (plot for Gibilmanna not shown here) and for all the analyzed seasons. This result agrees with that was found by Ezquer et al. (2014), Lee and Reinisch (2012), and Liu et al. (2011, 2012). On the contrary, it does not agree with that reported by Araujo-Pradere et al. (2011) who did not find a decrease of *Nm*F2 for the last minimum with respect to the minimum 22/23, for the mid-latitude station of Point Arguello (42.3°N, 239.4°E, USA).

Table 3 shows the seasonal relative percentage variations (averaged over 24 h) between minima 21/22 and 23/24 (for Rome, Gibilmanna and Tucumán), and between minima 22/23 and 23/24 (only for Rome). The values for the relative percentages were calculated using the relation $(NmF2_{min\ 23/24} - NmF2_{min\ A})/NmF2_{min\ A} \cdot 100$, where A can represent the minimum 21/22 or 22/23. It is clearly visible that the decrease between the last minimum and the minimum 21/22 is more pronounced at low latitudes (yearly mean decrease of −32% for Tucumán) than at mid latitudes (yearly mean decrease of −20% and −12% for Rome and Gibilmanna respectively). Considering the same minima, a significant difference can also be observed between the results of Rome and Gibilmanna; however,

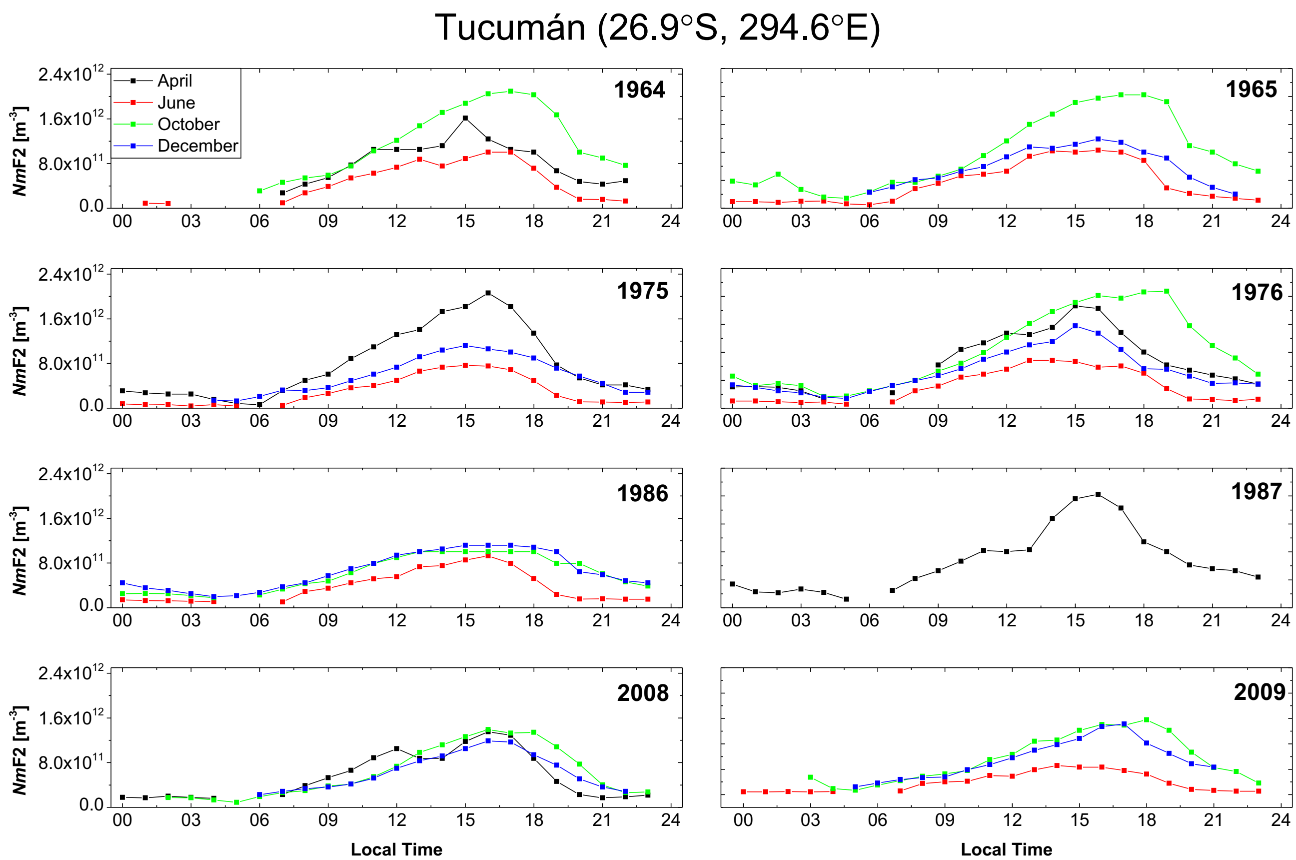

Fig. 5. Same as Fig. 4 for Tucumán.

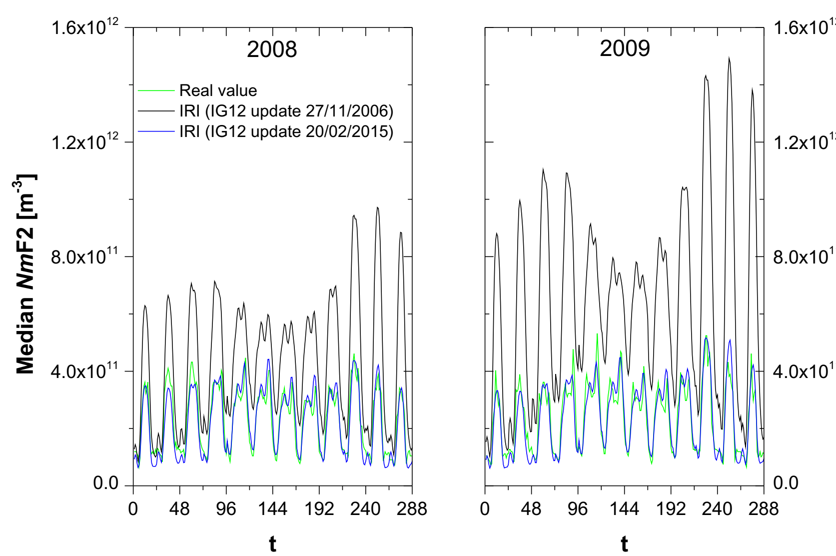

Fig. 6. Observed hourly monthly median values of $NmF2$ (green) for the years 2008 and 2009 compared with those given as output by IRI by considering values of the IG12 index updated on (blue) 20/02/2015 and on (black) 27/11/2006, for Rome station. The parameter t on the x axis is defined so that $t = 0$ identifies the 00:00 LT of January and $t = 288$ identifies the 23:00 LT of December. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

this might be due to the lack of data characterizing Gibilmanna in March and June.

In detail, from Table 3 and Fig. 2, it is possible to observe that at Rome the decrease between the minimum 21/22 and the minimum 23/24 is more pronounced than that between the minimum 22/23 and the last minimum, showing a monotone decreasing trend of $NmF2$ for the last three solar cycles. A similar decreasing

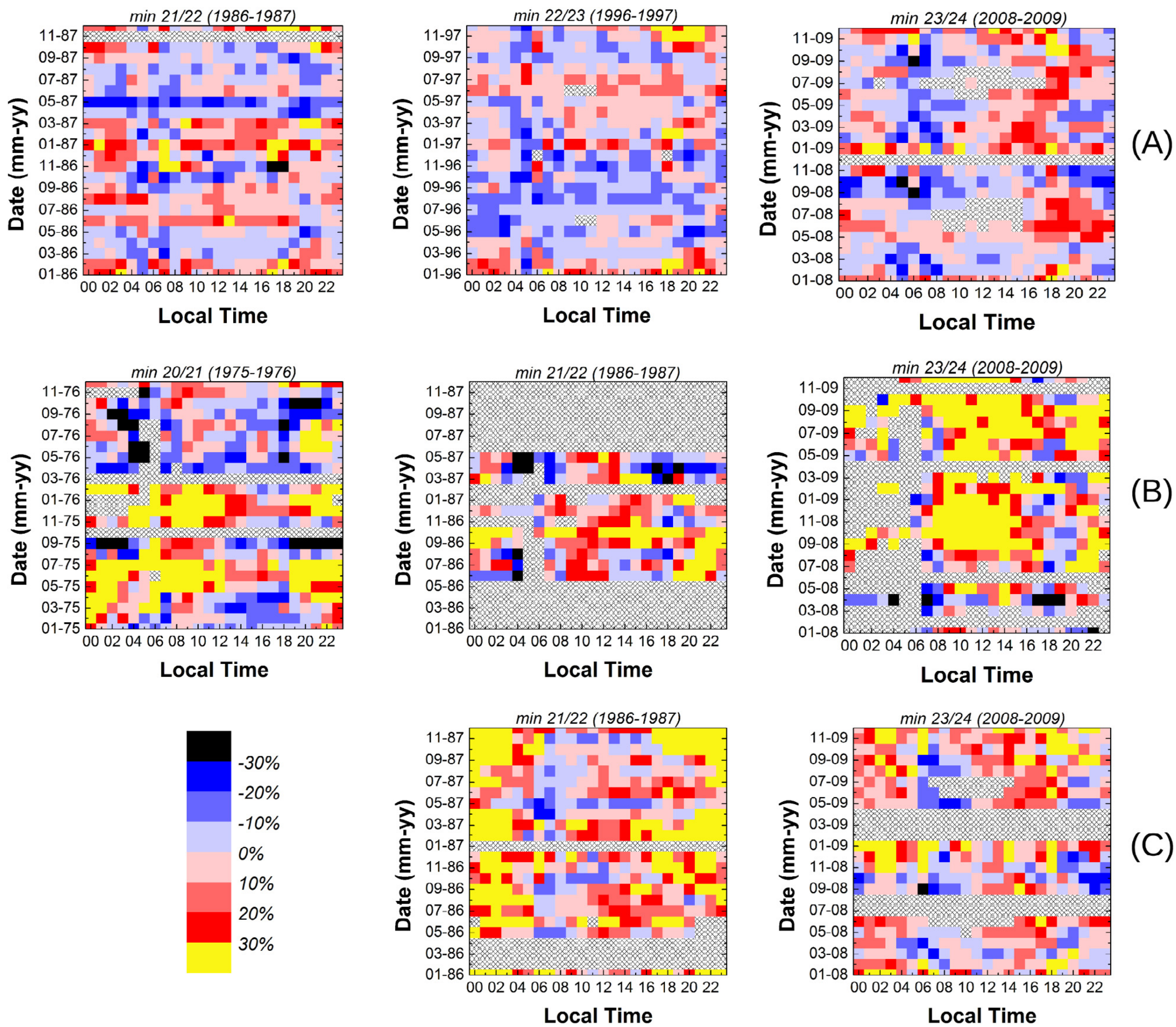

Fig. 7. Relative percentage difference maps, according to Eq. (2), for (A) Rome, (B) Tucumán, and (C) Gibilmanna, for recent solar minima. Gray areas refer to lack of measured values.

Table 2
Mean percentage distance ($|\overline{PD}(\%)|$) of NmF2 between measured values and IRI outputs for the recent minima. The distances are averaged on the 24 h and on the two years included in each minimum.

IRI-Real value mean distance	Min 19/20 (%)	Min 20/21 (%)	Min 21/22 (%)	Min 22/23 (%)	Min 23/24 (%)
Rome	11	12	11	10	11
Gibilmanna	–	–	25	–	15
Tucumán	20	25	21	–	29

pattern can be observed for all seasons, the most pronounced decrease being observed for the June Solstice for the nighttime range 21–04 LT (mean decrease of −43% between minima 21/22 and 23/24, and −27% between minima 22/23 and 23/24). Nevertheless, considering all the seasons, the largest decreases are visible during the local sunset hours 16–18 LT (−28% between minima 21/22 and 23/24 and −24% between minima 22/23 and 23/24), while the lowest decreases occur at local sunrise hours 6–7 LT (+7% between minima 21/22 and 23/24 and −9% between minima 22/23 and 23/24). The station of Gibilmanna is characterized by similar results, with percentage variations less pronounced than for Rome.

Considering daytime hours (9–18 LT), it is observed an important decrease during December Solstice between minima 21/22 and 23/24 for both Rome and Gibilmanna (mean decrease of −32% and −21% respectively).

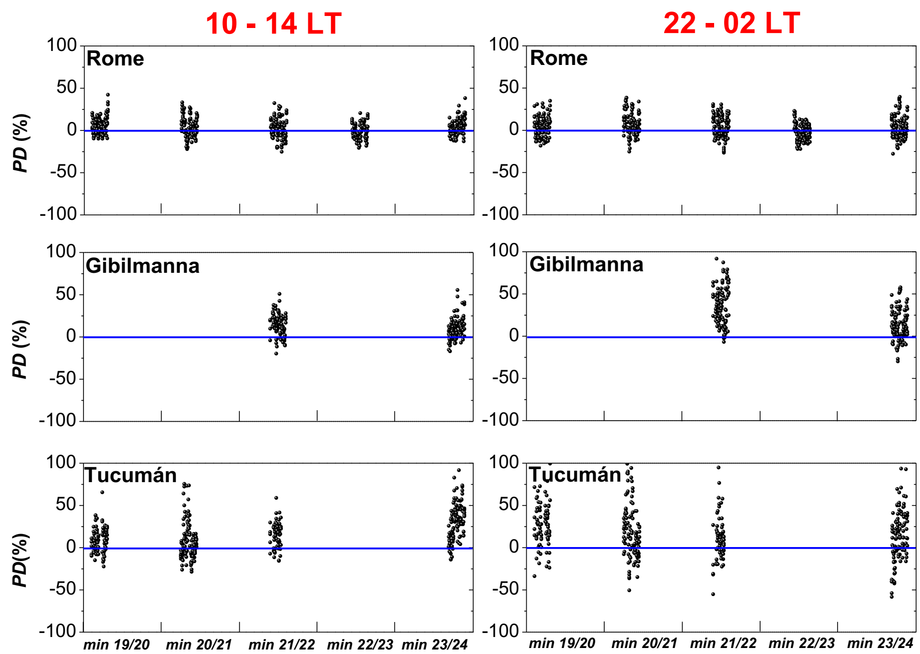

Fig. 8. Relative percentage differences according to Eq. (2), for recent solar minima, for Rome, Gibilmanna, and Tucumán, for daytime hours (10–14 LT) and nighttime hours (22–02 LT). The blue horizontal line identifies the zero. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Relative percentage variations averaged on 24 h. The percentage is calculated using the relation $((NmF2_{min23/24} - NmF2_{minA})/NmF2_{minA}) \cdot 100$, where A can represent the minimum 21/22 or 22/23. The values used for NmF2 are the seasonal median, calculated as described in Section 3 and plotted in Figs. 2 and 3.

	March Equinox (%)	June Solstice (%)	September Equinox (%)	December Solstice (%)	Yearly mean (%)
min 23/24 – 21/22 comparison					
Rome	−18	−21	−21	−21	−20
Gibilmanna	−3	−16	−13	−16	−12
Tucumán	−38	−39	−31	−18	−32
min 23/24 – 22/23 comparison					
Rome	−12	−18	−21	−19	−18

For the low-latitude station of Tucumán, Fig. 3 and Table 3 show a different pattern. Comparing minima 21/22 and 23/24, it is possible to observe that the most prominent decreases are measured for March Equinox, June solstice and September Equinox (mean decrease of −38%, −39% and −31% respectively), while the decrease for the December Solstice is substantially lower (−18%). Considering the comparison between the same two minima, it is clear that the decrease for the low-latitude station of Tucumán is larger than that observed at the mid-latitude stations of Rome and Gibilmanna (comparing the values of the last column of Table 3). An hourly NmF2 based analysis shows for Tucumán a clear pattern with more pronounced decreases during nighttime hours (21–06 LT) than for daytime hours (07–20 LT) for all the seasons. Averaging over the time intervals 21–06 LT and 07–20 LT, percentage decreases of −45%/−33%, −51%/−32%, −41%/−26% and −22%/−17% are obtained for March Equinox, June Solstice, September Equinox and December Solstice, respectively.

Using monthly median values, available also for the minima 19/20 and 20/21 for Rome and Tucumán, it is possible to analyze two characteristic ionospheric anomalies: the winter anomaly and the semi-annual anomaly. Figs. 4 and 5 show the monthly median values for April, June, October and December, for the years of recent minima, as recorded at Rome and Tucumán respectively. In order to distinguish the contribution of the solar activity to the seasonal differences shown by the NmF2 values in Figs. 4 and 5, Table 4 reports the monthly mean sunspot numbers of April, June, October and December for the last 5 solar minima.

For the mid-latitude station of Rome, it is interesting to note that the winter anomaly is not visible for both years (2008 and 2009) characterizing the minimum 23/24, while it is visible for minima 22/23, 21/22, 20/21, and for the year

Table 4
Monthly mean sunspot numbers of April, June, October and December for the years of the last 5 solar minima.

Year	April	June	October	December
1964	12.9	13.5	9.2	22.1
1965	10.2	23.3	29.1	24.7
1975	7.7	16.7	13.6	11.6
1976	27.3	17.9	29.7	22.3
1986	22.4	0.6	40.1	5.1
1987	46.0	18.8	63.4	29.1
1996	6.8	16.5	0.7	14.0
1997	23.0	20.8	32.8	55.5
2008	3.6	5.2	4.2	1.0
2009	1.2	6.3	7.7	16.3

1964 of the minimum 19/20. Hence, it was confirmed that at mid latitudes the winter anomaly tends to disappear when the solar activity decreases. The fact that this anomaly is not visible at all for the two years of the last minimum proves the particular response of the ionospheric plasma to the last anomalous solar minimum. The same phenomenon is recorded at Gibilmanna.

For the low-latitude station of Tucumán the situation is quite different, with the winter anomaly which is never visible. However, as mentioned, the anomaly is less visible at low latitude and in particular in the south hemisphere, so this is not an unexpected result.

Another ionospheric feature that can be analyzed from Figs. 4 and 5 is the semi-annual anomaly. Concerning Rome, this anomaly is clear for October, and less obvious for April, anyhow its amplitude tends to decrease for the last solar minimum. At Tucumán the anomaly is clearly visible for minima 19/20 and 20/21, while it is not clearly visible for the year 1986 and for the last minimum. In fact in 2008 and 2009 similar values for October and December are observed at local noon.

The results of this section confirm then the particular conditions of the ionosphere in conjunction with the last solar minimum both at low and mid latitudes. In accordance with the study by Liu et al. (2011), it is confirmed that the more pronounced decreases of *Nm*F2 are visible at the typical latitudes of the equatorial ionization anomaly, where Tucumán is located. Moreover, it is confirmed that the winter and semi-annual anomalies tend to disappear as the solar activity decreases. Furthermore, underlining the peculiarity of the minimum 23/24, the typical mid-latitude phenomenon of the winter anomaly is completely absent during the last solar minimum at Rome and Gibilmanna stations.

4.2. Comparison with IRI-2012

Fig. 7 plots the parameter $PD(\%)$ according to Eq. (2) for Rome, Gibilmanna, and Tucumán, for the recent minima. The total mean percentage distances (mean over 24 h and over the 2 years of every minimum) are reported in Table 2 for all the available minima and for all the stations. The most important result, clearly visible from Fig. 7 and confirmed by the values of Table 2, is that IRI works better at mid latitudes (Rome and Gibilmanna) than at low latitudes (Tucumán). This effect is particularly visible for the minimum of cycle 23/24, where a total mean percentage distance of 29% is observed for Tucumán, while lower values of 15% and 11% are observed for Gibilmanna and Rome. The general good correspondence found for the last minimum at mid latitudes, between observed values and IRI outputs, confirms what was shown by both Zakharenkova et al. (2013) and Bilitza et al. (2012). The lower accuracy found at the low-latitude station of Tucumán than at the mid-latitude stations of Rome and Gibilmanna agrees with the results of Bilitza et al. (2012), Lee and Reinisch (2012) and Adebesin et al. (2014).

An important result emerged from the analysis is that at mid latitudes there is not a clear loss of accuracy of the IRI model for the last minimum with respect to the previous ones. For Rome, the IRI model works approximately in the same way for the last five solar minima periods as it is shown in Table 2. Unexpectedly, for Gibilmanna better results are obtained for the last minimum with respect to the minimum 21/22. A slightly different result is obtained for the station of Tucumán. A higher total mean percentage distance is observed for the last solar minimum (29%) than respect to the previous ones. Anyhow, this worsening (4% with respect to the minimum 20/21), is not so significant and might not be due to the particularity of the last solar minimum.

Looking at Fig. 7 and focusing our attention on the last minimum, it is interesting to note that for Rome and Gibilmanna there is an IRI tendency to underestimate the observed values for the sunrise hours (05–08 LT), while an opposite trend is visible for the sunset hours (17–19 LT). No clear seasonal patterns can be inferred from Fig. 7 for both stations. Comparing with the results of Section 4.1, it is interesting to observe that the underestimation made by IRI for sunrise hours corresponds to the hours where the lower decreases are observed in the inter-minima comparison. Likewise, the tendency of IRI to overestimate at sunset hours coincides to the more pronounced decreases in inter-minima comparison.

For Tucumán, for the minimum 23/24, there is a general tendency of IRI to overestimate the observed values. This effect is particularly accentuated starting from September 2008 until the end of 2009. Zones of underestimation are visible during nighttime hours (00–03 LT) from January 2008 to August 2008 and from March 2009 to August 2009.

Fig. 8, showing plots of the $PD(\%)$ parameter for the recent minima for Rome, Gibilmanna and Tucumán, helps us to make a comparison between IRI and observations for daytime and nighttime hours. For Rome, the IRI model does not show particular features, with equivalent zones of overestimation and underestimation, with the $PD(\%)$ values always within the range ±30%. For nighttime hours, a slightly more pronounced overestimation of IRI is visible, in particular for minima 19/20, 20/21 and 21/22, even though the effect is somewhat weak. This result is quite in accordance with the outcomes shown by Bilitza et al. (2012).

Surprisingly, the situation is quite different for Gibilmanna, where a steady and significant overestimation made by IRI is observed for both daytime and nighttime hours.

For Tucumán, the IRI model substantially overestimates the measured values of *Nm*F2 for all the analyzed minima and for both daytime and nighttime hours. This result again is in accordance with what was found by Bilitza et al. (2012) for daytime hours by considering data recorded at the station of Cachoeira Paulista (22.7°S, 45.0°W, Brazil) that, similarly to Tucumán, is located close to the south crest of the equatorial ionization anomaly. In both cases, values of *PD*(%) bigger than 40–50% are observed.

5. Conclusions

There is no doubt that the last minimum of solar activity was anomalous and represented a very good opportunity to study the response of the ionospheric plasma to extreme solar conditions. In this study, focused on the maximum of electron density, *Nm*F2, a decrease of values for the last minimum with respect to the previous ones was observed for all the three considered stations: Rome and Gibilmanna at mid latitudes, and Tucumán at low latitudes. A latitude dependence is observed, with a more pronounced decrease at low latitudes with respect to mid latitudes. An analysis based on seasonal median values reveals that at mid latitudes the decrease is more pronounced from June to December solstices, with slightly lower decreases for the March equinox. The hours of the day for which the decrease is bigger are near the sunset (16–18 LT), while less pronounced decreases are observed around sunrise hours (6–7 LT). On the contrary, at low latitudes the largest decrease is visible during the period from March to September equinox, with a clear more pronounced decrease during nighttime hours (21–06 LT).

Moreover, at mid-latitude stations, the winter anomaly was not recorded for the last minimum (years 2008–2009), confirming the anomalously low level of solar activity during this period. At Tucumán, the semi-annual anomaly, clearly visible for the minima 19/20 and 20/21, becomes less visible for the minimum 23/24.

A comparison between IRI outputs and measured monthly median values for the recent solar minima reveals that both at mid and low latitudes the model does not worsen its performance for the last minimum with respect to the previous ones.

The most relevant result is that, for low and very low solar activities, IRI provides a reliable output at mid latitudes. On the contrary, the model shows a clear loss of reliability at low latitudes. From this point of view, the very particular position of Tucumán, situated exactly on the south crest of the equatorial ionization anomaly, plays a key role. Hence, this result suggests that IRI needs to be continuously tested, in particular at locations near the equator and the crests of the equatorial ionization anomaly, in order to improve the reliability and capability of the model to describe and forecast the most important ionospheric parameters at these ionospherically crucial latitudes.

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