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Behaviour of ionospheric magnitudes of F2 region over Tucumán during a deep solar minimum and comparison with the IRI 2012 model predictions

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ABSTRACT

In this paper we analyze the behaviour of the critical frequency of the F2 region of the ionosphere (foF2) and the height of the maximum density of free electrons in F2 region (hmF2) over Tucumán (26.9°S, 294.6°E), during the deep solar minimum occurred in 2008–2009. Data used were compared with those obtained at solar minimum observed in 1975–1976

In addition, we check the validity of the International Reference Ionosphere model (IRI), in the version 2012, to predict the maximum free electron density in the ionosphere (NmF2) above the mentioned station, for very low solar activity.

The results show that: (a) Ionization was lowest for recent solar minimum. (b) The semmianual anomaly which are present in the behaviour of foF2 at times of increased solar activity, was not clearly observed during the period 2008–2009. This phenomenon could be related with the very low solar activity for that period, confirming the relationship of the amplitude of this anomaly with the solar activity reported by other authors. (c) In most cases, the values of hmF2 recorded in the deep solar minimum are lower than those observed in the period 1975–1976, suggesting a decrease in the height of the ionosphere in the course of time, which could be related to the greenhouse effect in the atmosphere and the anomalously low solar extreme-ultraviolet irradiance. (d) IRI predictions show significant deviations from the experimental values, indicating the need for improvements in the model.

1. Introduction

It is well known that high frequency (HF) radio signals render possible long distance communication in all time for 24 h a day, with a low cost. The ionosphere is of primary importance for HF propagation, reason why measurements of ionospheric characteristics are of great interest.

The ionospheric measurements at Tucumán (26.9ºS, 294.6ºE) began in 1957, the International Geophysical Year, when an analogical ionosonde was transferred from the Navy of Argentina to the National University of Tucumán (UNT). That ionosonde stopped working in 1987.

Many scientific studies were conducted with the measurements obtained by the ionosonde installed in 1957 (Ortiz de Adler et al., 1993; Ortiz de Adler and Manzano, 1995; De Ragone et al., 1997; Mosert de González et al., (1997); Ezquer et al, 1999, 2002a, 2002b, 2003, 2008; Mansilla et al., 2005 among others).

Within the Italian-Argentine collaboration supported by the Istituto Italo Latino Americano (IILA), in 2007, an Advanced Ionospheric Sounder (AIS) built at the Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, was installed at the Upper Atmosphere and Radiopropagation Research Center (CIASUR) of the Regional Faculty of Tucumán of National Technological University (UTN).

That ionosonde is equipped with Autoscala, a software able to perform an automatic scaling of the ionograms (Pezzopane and Scotto, 2005, 2007, 2008; Scotto and Pezzopane, 2008b). Fig. 1 shows AIS, and a corresponding ionogram obtained at CIASUR.

So, thanks to this new installation, we once again have ionosonde measurements after a gap of 20 years.

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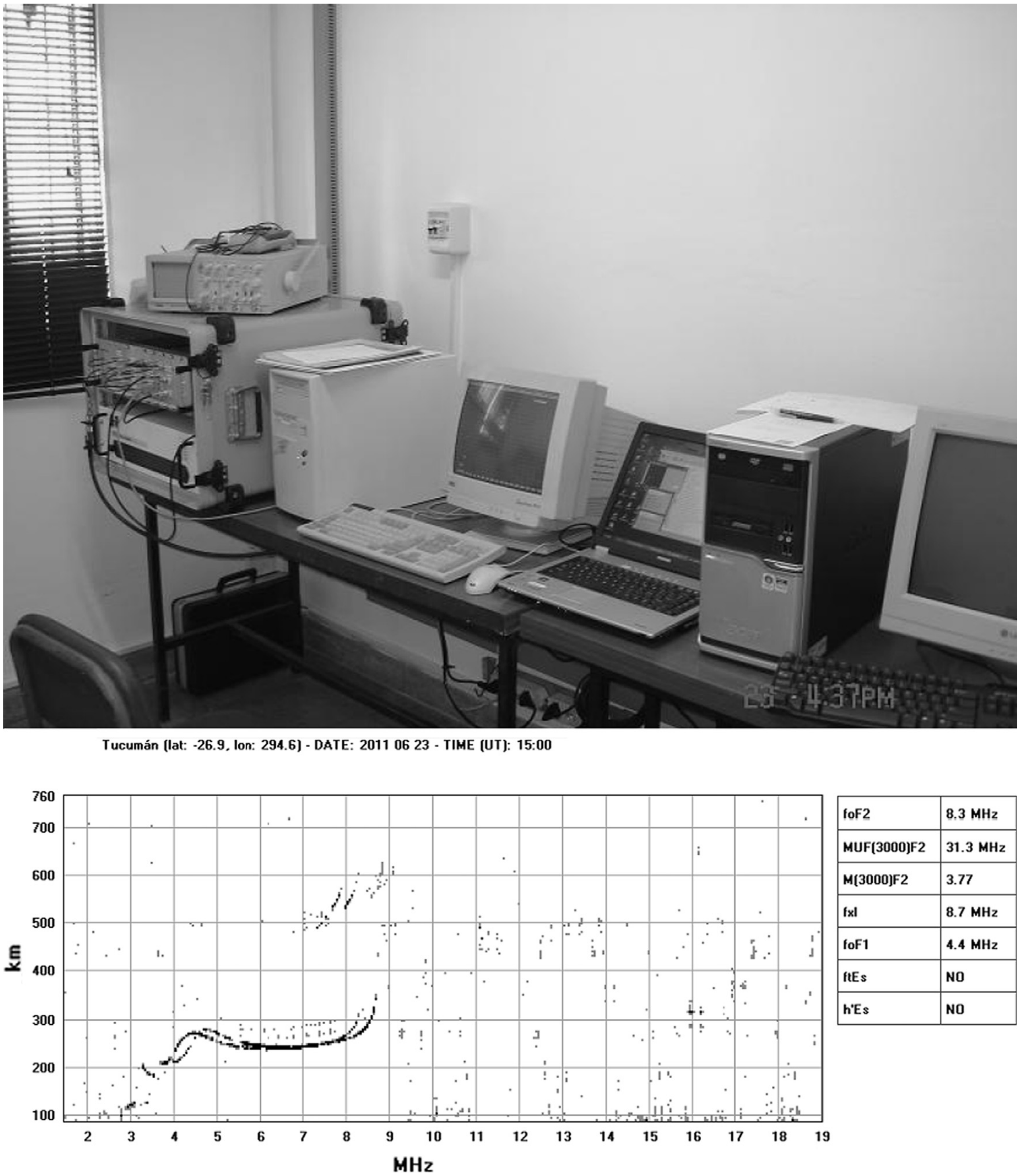

Fig. 1. AIS system installed at CIASUR and a corresponding recorded ionogram scaled by Autoscala.

Moreover, it is worth noting that the real time of the critical frequency of the F2 region of the ionosphere (foF2) values over Tucumán produced by the station are already being used by the Australian IPS Radio and Space Services for mapping purposes.

1.1. *Anomalies*

Equatorial anomaly: At the beginning of the first studies of the ionosphere, the behaviour of ionospheric characteristics was described by Chapman theory (Chapman, 1931) according which the ionization is controlled by the intensity of solar radiation and zenith angle. Behaviours that cannot be explained by the theory of Chapman are called “anomalies”. Early studies of these anomalies were made by Berkner et al (1936).

Characterized as the occurrence of a trough in the ionization concentration at the equator and crests at about 15º in magnetic latitude (Appleton, 1946) in each hemisphere, the equatorial anomaly has been described as arising from the electrodynamics at the equator. Since an electric field is established perpendicular to the magnetic field, an ExB/B^2 drift moves the ionization vertically upwards during the day and downwards at night. The upward motion of ionization during the day is termed the equatorial fountain, since ionization rises above the magnetic equator until pressure forces become appreciable that it slows down and under the force of gravity moves along the field lines and is deposited at higher tropical altitudes. The resulting enhancement of ionization at tropical latitudes and a through in ionization concentration at the magnetic equator is termed the equatorial anomaly. Tucumán is placed near the southern crest of the equatorial anomaly.

Annual anomaly: In the world as a whole, there is an annual variation of the maximum electron density of free electrons in the F2 region (NmF2), which is approximately 20% greater in December than in June. This value exceeds the 7% asymmetry in ion production due the annual variation of Sun-Earth distance. Rishbeth and Múller-Wodarg (2006) pointed out that though the annual anomaly was noticed in ionospheric data long time ago, it is still unexplained.

Winter anomaly: The values of foF2 at noon are higher in winter than in summer. It has been proposed that this anomaly is related to changes in the neutral composition of the atmosphere, generated by heating in the summer hemisphere and a subsequent convection of lighter neutral elements towards the winter sector, which causes changes in the ratio of [O]/[N2] in both hemispheres (Rishbeth and Setty, 1961; Johnson 1964; Torr and Torr, 1973). The decrease of solar activity leads to a decreasement of the energy input, which causes a reduction in the convection activation mechanism. Thus, it would be expected to this anomaly tends to disappear during low solar activity.

Semiannual Anomaly: it produces larger foF2 values for equinoxes than for solstices. This anomaly is observed in both high and low activity (Rishbeth and Garriot, 1969). It is most noticeable in low latitude (Yonezawa and Arima, 1959; Yonezawa, 1967, 1971; Torr and Torr, 1973). Several mechanisms have been proposed to explain this anomaly. Yonezawa (1971) proposed that the semiannual anomaly in foF2 is related with the variation of the upper atmosphere temperature. Torr and Torr (1973) suggested that this is due to semiannual variation in neutral densities associated with geomagnetic and auroral activity. Mayr and Mahajan (1971) showed that the semiannual anomaly requires significant variation in the neutral composition at lower height. Ma et al. (2003) suggested that the semiannual variation of the diurnal tide in the lower thermosphere induces the semiannual variation of the amplitude of the equatorial electrojet, this causes the variation of amplitude of ionospheric equatorial anomaly through fountain effect and this process induces the semiannual anomaly at low latitude. The amplitude of the semiannual anomaly has a close relationship with the solar activity. The amplitude of the semiannual anomaly in the years of solar maximum is larger than in the years of solar minimum Ma et al. (2003).

1.2. Long term trends

It is well known that ionospheric characteristics show long term trends which are often associated with the enhancement of the density of gases which produce the "greenhouse" effect in the atmosphere. These gases cause warming in the lower atmosphere. However, the effect on the stratosphere and above it is a cooling due to increased emission of infrared radiation from the upper atmosphere into space (Brasseur and Hitchman, 1988). Rishbeth (1990) suggested that this effect produces a reduction in the height of the maximum density of free electrons in F2 region (hmF2). Changes that would occur at altitudes between 60 and 450 km as a consequence of doubled CO_2 and methane are (Roble and Dickinson, 1989; Rishbeth, 1990; Rishbeth and Roble, 1992): (i) the thermosphere would cool by ~50 °K, (ii) the air density at heights of 200–300 km will be reduced by ~20–40%, (iii) The height of the ionospheric F2-layer peak will drop on average by about ~15–20 km.

Using long-term ionosonde measurements in middle and high latitudes in the northern and southern hemispheres, Bremer (1992), Ulich and Turunen (1997) and Jarvis et al (1998) found a decrease in the height of the ionosphere. The study of Bremer (1992) revealed a downward trend in hmF2 of 0.24 km/ year. Lastovicka et al. (2006) showed that the trends in foF2 are very small, of the order of −0.01 MHz/year. Using 30 years of data obtained at Tucumán with our first ionosonde Elías and de Adler (2006) observed that foF2 decreased about 2 MHz.

1.3. Anomalously low solar extreme-ultraviolet irradiance

Using global-average thermospheric total mass density, derived from the drag effect on the orbits of many space objects, Emmert et al (2010) found that during 2007–2009 thermospheric densities at altitude of 400 km were the lowest observed in the 43 year database, and were anomalously low. They show that the average density at 400 km during the year surrounding the cycle 23/24 minimum was 29% lower than the corresponding average density during the cycle 22/23 minimum. About 10% (i.e., one third) of this 29% is attributable to lower F10.7 values during the cycle 23/24 minimum. The remaining 19% (two thirds) of the 29% difference was considered anomalous (Emmert et al, 2010) i.e., not attributable to the estimated climatological effect of prolonged low levels of solar EUV irradiance (for which F10.7 is a proxy) or geomagnetic activity during the cycle 23/24 minimum.

Model simulations suggest that 3% would be caused by greater CO_2 cooling than during the cycle 22/23 minimum (Qian et al, 2006). Emmert et al (2010) suggested that the long term relationship between EUV irradiance and F10.7 has changed markedly during recent years, with EUV levels decreasing more than expected from the F10.7 proxy, resulting in less thermospheric heating. This represents a solar (rather than terrestrial) anomaly. These authors reported that internal processes of the mesosphere and the thermosphere changes in the chemistry and dynamics in combination with anthropogenic disturbances could be also candidates to explain the observed density changes.

Secular change due to increase levels of CO_2 and other greenhouse gases, which cool the upper atmosphere, also plays a role in the thermospheric climate, and changes in geomagnetic activity could also contribute to the lower density observed from satellite drag data corresponding to 2007–2009 (Solomon et al, 2011). These authors performed a study to confirm that low solar EUV irradiance is the primary cause of the anomalously low thermospheric density, but also to quantify the roles played by other contributing factors. Their results show that CO_2 and geomagnetic activity play small roles, and the primary cause of the low temperatures and densities remains the unusually low levels of solar EUV irradiance.

Deng et al (2012) extended the studies on the causes of low thermospheric density during the last solar minimum. They examined the variation of the energy budget to the Earth's upper atmosphere during last solar cycle from both solar EUV irradiance and geomagnetic activity. Their model simulations indicate that the solar irradiance and geomagnetic energy variations account for 3/4 and 1/4 of the total neutral density decrease in 2008, respectively.

If EUV decreased a reduction in the ionization of the ionosphere would be expected. It has been reported that foF2 from ionosonde data was lower in 23/24 solar minimum than 22/23 at some locations (Chen et al, 2011; Liu et al 2011) indicating that some changes did occur. Even though the ionosphere response to the recent solar minimum was the first evidence that something was different, this may have been due more to reduction of ionospheric altitude than topside densities. Owing to the lower observed density, reduction in ionospheric altitudes must have occurred, regardless of the causative mechanism (Solomon et al, 2011).

1.4. International reference ionosphere model (IRI)

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

The need for predicting the behaviour of the ionosphere leads to modelling of that atmospheric region. Several models (e.g. Chiu, 1970; Anderson, 1973; Llewellyn and Bent, 1973; Bent et al., 1976; Anderson et al., 1987; Bilitza, 1990; Ezquer et al., 1992, 1994, among others) were developed to predict the behaviour of the ionospheric parameters. Empirical models are widespread tools to describe ionospheric conditions. Nowadays, these models are used not only for the long-term prediction but also for the real-time description of the ionospheric conditions. One of the most widely used empirical models is the IRI (Rawer et al., 1978, Bilitza 1990, 2001; Bilitza and Reinisch, 2008). IRI model is actively used in a great variety of applied and research projects. In particular, IRI provides a basis for the simulation and prediction of the ionospheric radio wave propagation. The model takes into account daily and seasonal variations, perturbed and quiet conditions as well as the impact of the solar activity on the ionospheric plasma.

The IRI model uses a ionospheric-effective solar index that is based on ionosonde measurements, the IG12 index, to obtain NmF2 (Bilitza et al, 2012).

Ionospheric measurements are essential to know the behaviour of the ionosphere and also to check the validity of the ionospheric models.

This paper discusses the behaviour of foF2 and hmF2 over Tucumán during the deep solar minimum occurred in 2008–2009 and the validity of the IRI 2012 model to predict NmF2 over the mentioned station, for very low solar activity

2. Data

Fig. 2 shows the periods of measurements of both ionosondes of Tucumán.

In this work, foF2 and propagation factor M3000F2 (used for the hmF2 calculation) values corresponding to the old ionosonde were scaled by hand. Those corresponding to AIS were automatically scaled by Autoscala. Concerning the ionospheric characteristics of the F2 region, Autoscala proved to be reliable (Pezzopane et al, 2007), and this reliability is increased in the last years because of the several filters that have been added and hence used by the image processing technique of Autoscala (Scotto and Pezzopane, 2008a; Pezzopane and Scotto, 2010).

We consider equinoxes and solstices data corresponding to the low solar activity years 1975, 1976, 2008 and 2009. In this work the median is used as a monthly value because it has the advantage of being less affected by large deviations in the value of the ionospheric characteristics that can occur during magnetic storms. The hourly monthly median values were calculated by considering a number of days greater than 15. The smoothed sunspots number for the considerer months are shown in Table 1. In it we can see that the smoothed sunspot number (Rz12) for 1975–1976 ranges between 12.2 and 18.6 while for the deep solar minimum Rz12 reaches values as low as 1.7. These low values indicate the large number of spotless days during 2008 and 2009, as the Rz12 value is averaged over 12 months

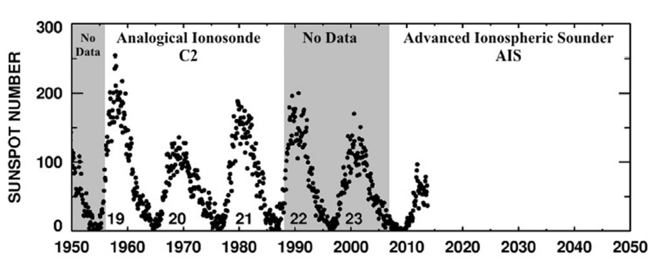

Fig. 2. Periods of measurements of both ionosondes of Tucumán.

Table 1
Rz12 values of April, June, October and December for the years 1975, 1976, 2008, and 2009.

Months	RZ 12 Years			
	1975	1976	2008	2009
April	18.6	12.6	3.4	2.2
June	16	12.2	3.3	2.7
October	15.4	13.4	1.8	7.1
December	16.2	14.8	1.7	8.3

3. Results and discussion

3.1. Behaviours of foF2 and hmF2

Fig. 3 shows hourly monthly median values of foF2 corresponding to April (equinox), June (winter), October (equinox) and December (summer) for each year. There are no data for some cases. It can be seen a daily variation with a minimum at pre dawn hours and maxima values at afternoon hours, in all the cases (16 UT = 12 LT). Moreover, for the considered years the values corresponding to winter (June) are always lower than those corresponding to summer (December) indicating that the winter anomaly is not observed, as expected because of the low solar activity.

Related to the semiannual anomaly, the data obtained with the old ionosonde clearly show its presence for hours around the time of maximum ionization. For 2008 and 2009, years of very low solar activity, the foF2 monthly median values corresponding to summer are close to those of equinoxes. For 2008 the highest foF2 values of December (corresponding to 20 and 21 UT) are similar to those corresponding to equinoxes. For 2009 the highest foF2 values of summer (17 to 23 UT) are in the middle of those corresponding to equinoxes. They are greater than the values obtained during April. These results suggest that semiannual anomaly was not clearly present during the deep solar minimum, particularly for 2009.

Fig. 4 shows the data ordered by months. It can be seen that for April, June and October, the foF2 values of 2008 and 2009, in general, are lower than those corresponding to 1975 and 1979. For some cases the foF2 diminution reaches values as high as ∼2–3 MHz. Nevertheless, the data of December of 2008 and 2009 are similar to those of 1975. In other words, the December values corresponding to the deep solar minimum did not decreased as those values corresponding to the other months avoiding a clear development of the semiannual anomaly. This would be in agreement with the fact that the amplitude of this anomaly tends to decrease during low solar activity (Ma et al., 2003). In other words, the fact that the semiannual anomaly was not clearly developed could be due to the very low solar activity for the considered data.

In IRI the correlation between hmF2 and the propagation factor M3000F2 is used to model the F2-peak height (Bilitza et al, 2012). In this work M3000F2 measurements were used as input parameter in IRI-2012 model to calculate hmF2 values. The behaviour of this height is shown in Fig. 5. In general, it can be seen lower values for 2008–2009 than for 1975–1976, suggesting a cooling of the ionosphere during the deep solar minimum, result in agreement with those of Emmert (2010). For some cases the hmF2 diminution reaches values as high as ∼20–40 km.

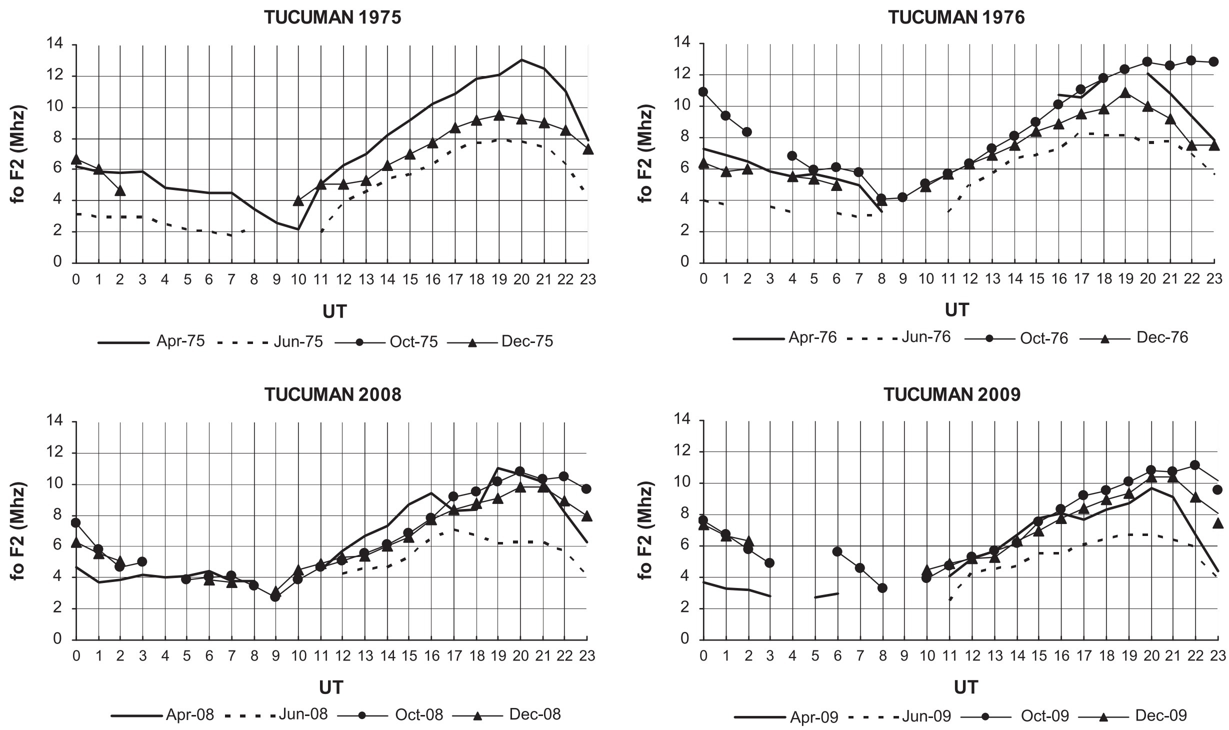

Fig. 3. Hourly monthly median values of foF2 corresponding to April (equinox), June (winter), October (equinox) and December (summer). 1975, 1976, 2008 and 2009. 16 UT=12 LT.

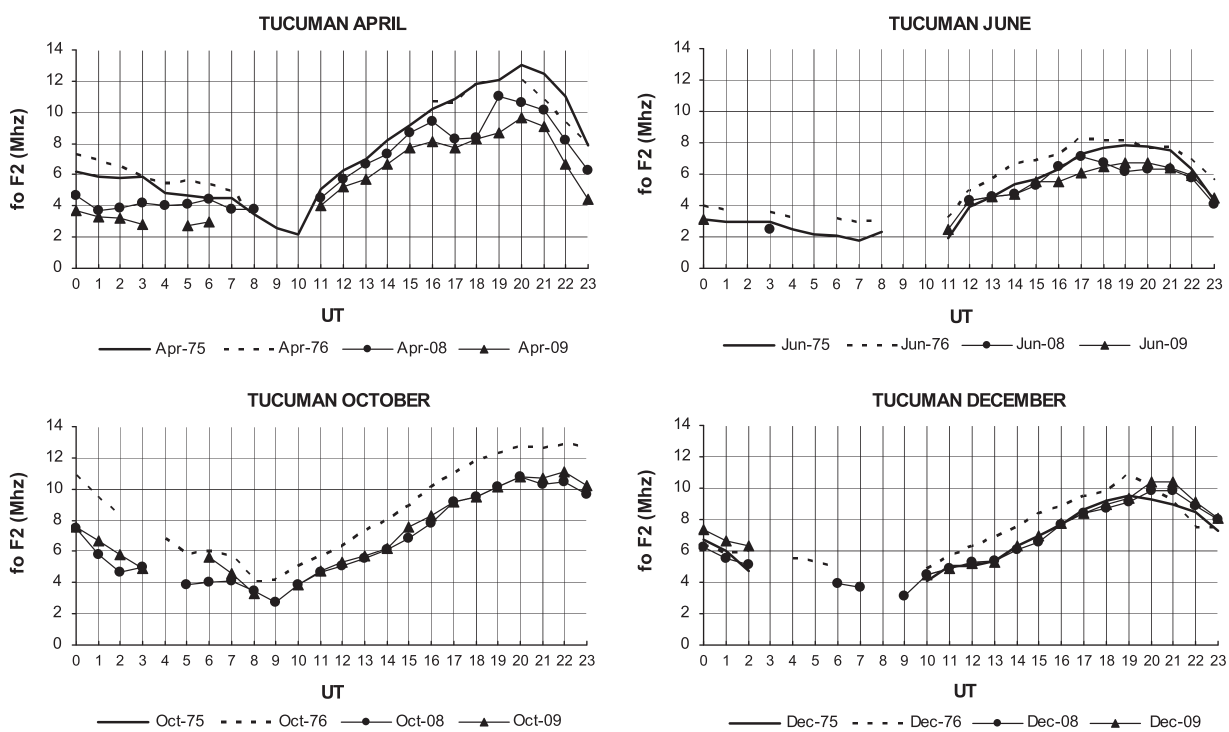

Fig. 4. Same as Fig. 3 but ordered by months.

Assuming a rate of decrease in hmF2 equal to - 0.24 km/year (Bremer 1992), along 34 years (1975 to 2009), the decrease in hmF2 would be ΔhmF2$=-8.5$ km. However, the results of the present work show cases with greater decrease ($\sim$20–40 km).

Moreover, a rate of decrease in foF2 equal to -0.01 MHz/year (Lastovicka et al 2006), would produce a diminution equal to ΔfoF2$=-0.34$ MHz along 34 years. Nevertheless, data from this study show cases with greater decrease values ($\sim$2–3 MHz) which are also greater than that observed by Elías and de Adler (2006) at Tucumán in a previous work ($\sim$2 MHz).

These results could be due to a combined effect of the long term trend and the anomalously low solar extreme-ultraviolet irradiance, which represents a solar anomaly (Emmert et al, 2010).

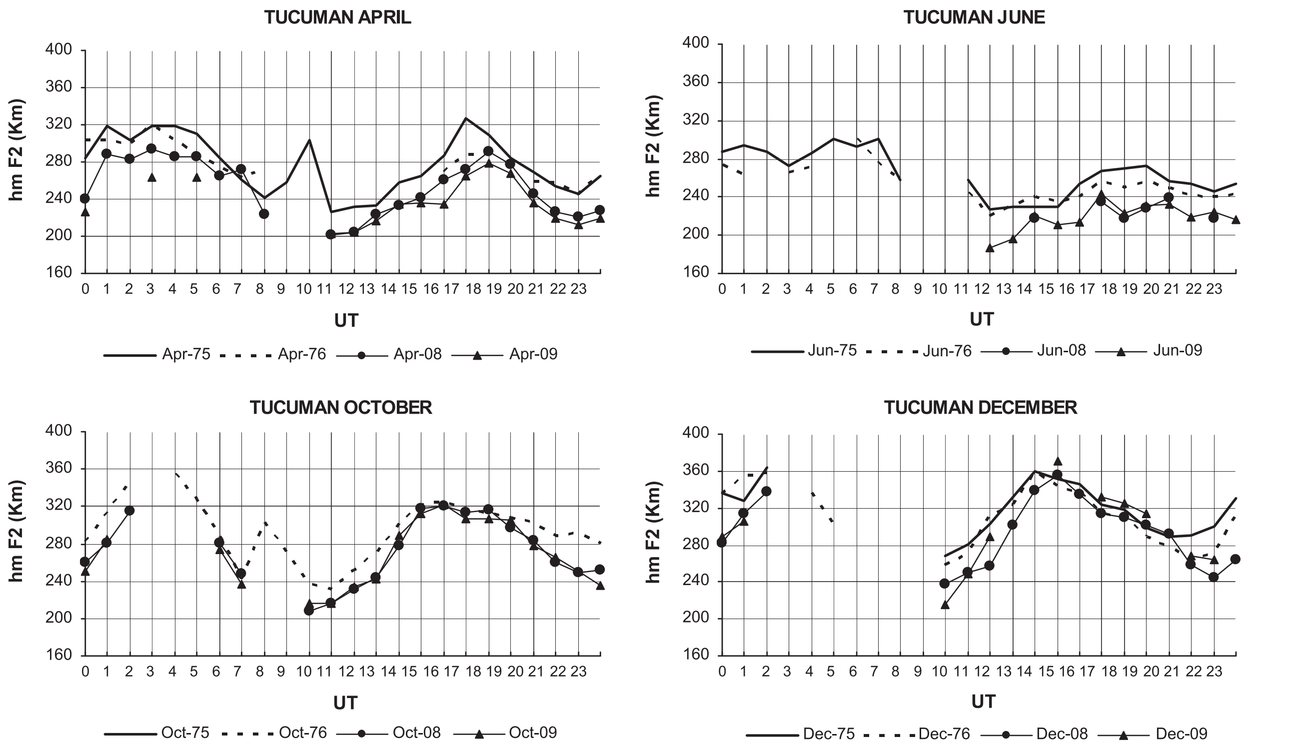

Fig. 5. Hourly monthly median values of hmF2 corresponding to April (equinox), June (winter), October (equinox) and December (summer). 1975, 1976, 2008 and 2009. 16 UT = 12 LT.

3.2. *IRI predictions*

Using data obtained with the old ionosonde of Tucumán, Ezquer et al. (2008) checked the validity of IRI model to predict NmF2 over Tucumán. Data corresponding to different months and solar activities were considered. For low solar activity, their results showed good URSI predictions for nighttime hours at solstices. The greatest deviations among predictions and measurements were observed from 9 UT to 11 UT reaching values greater than 50%. These authors also found that, in general, the predictions obtained with CCIR and URSI were similar. Moreover, their results showed that, at equinoxes and for low solar activity, the greatest disagreements among predictions and measurements were observed since 8 UT to 14UT reaching values close to 50%.

In this work, we present the performance of IRI 2012 as predictor of NmF2 over Tucumán for the very low solar activity years 2008 and 2009. We consider April (equinox), June (winter), October (equinox) and December (summer). To this end, the median is used as a monthly value because it has the advantage of being less affected by large deviations as those that can occur during magnetic storms.

NmF2 was calculated according to the well-known following equation:

$$NmF2 = 1.24 \times 10^{4} \times \text{fo F2}^{2} \quad (1)$$

where NmF2 is in cm^{-3} and foF2 is in MHz.

We calculated the deviation among modeled and experimental values as

$$D\% = [(\text{modeled value} - \text{experimental value})/(\text{experimental value})] \times 100 \quad (2)$$

For the worldwide description of the peak electron density, the International Radio Consultative Committee (CCIR) coefficients (1967a, 1967b) and the URSI coefficients (Rush et al., 1989) are used as choices in the IRI model.

In this work, CCIR and URSI choices are used in IRI to obtain modeled values of NmF2. The experimental value of NmF2 were obtained by Eq. (1) after introducing in it the foF2 value scaled from the ionogram recorded by the AIS ionosonde.

Fig. 6a and b shows the obtained results for 2008. It can be seen that there is no good predictions for nighttime hours as observed in a previous work (Ezquer et al 2008).

For April 2008, in general few cases have absolute deviation greater than 20%.

For June 2008 absolute deviations greater than 20% are observed.

URSI option overestimates NmF2 from 0 UT to 23 UT for October 2008, reaching values greater than 50% for many cases. Overestimations using CCIR coefficients are also observed.

As for October, the results for December show an evident overestimation given by the model since 12 UT to 19 UT using both mentioned options for NmF2. Deviations as high as 60% are observed for daylight hours.

The results for 2009 are similar to those of 2008 except for April where the deviations are greater than those corresponding to 2008 (see Fig. 7a and b).

Furthermore, with the exception of April 2008, in general, the model overestimates NmF2, a result that could be related with anomalously low solar extreme-ultraviolet irradiance

In summary, the deviations between modelled and measured NmF2 values corresponding to 2008 and 2009 are generally greater than those observed for low solar activity in a previous work (Ezquer et al, 2008).

4. Conclusions

(a) The values of foF2 have a daily variation with a minimum at pre dawn hours and a maximum after noon. (b) Lowest foF2 values were recorded for winter. (c) Ionization was lowest for recent solar minimum. (d) The winter anomaly was not observed, which is an

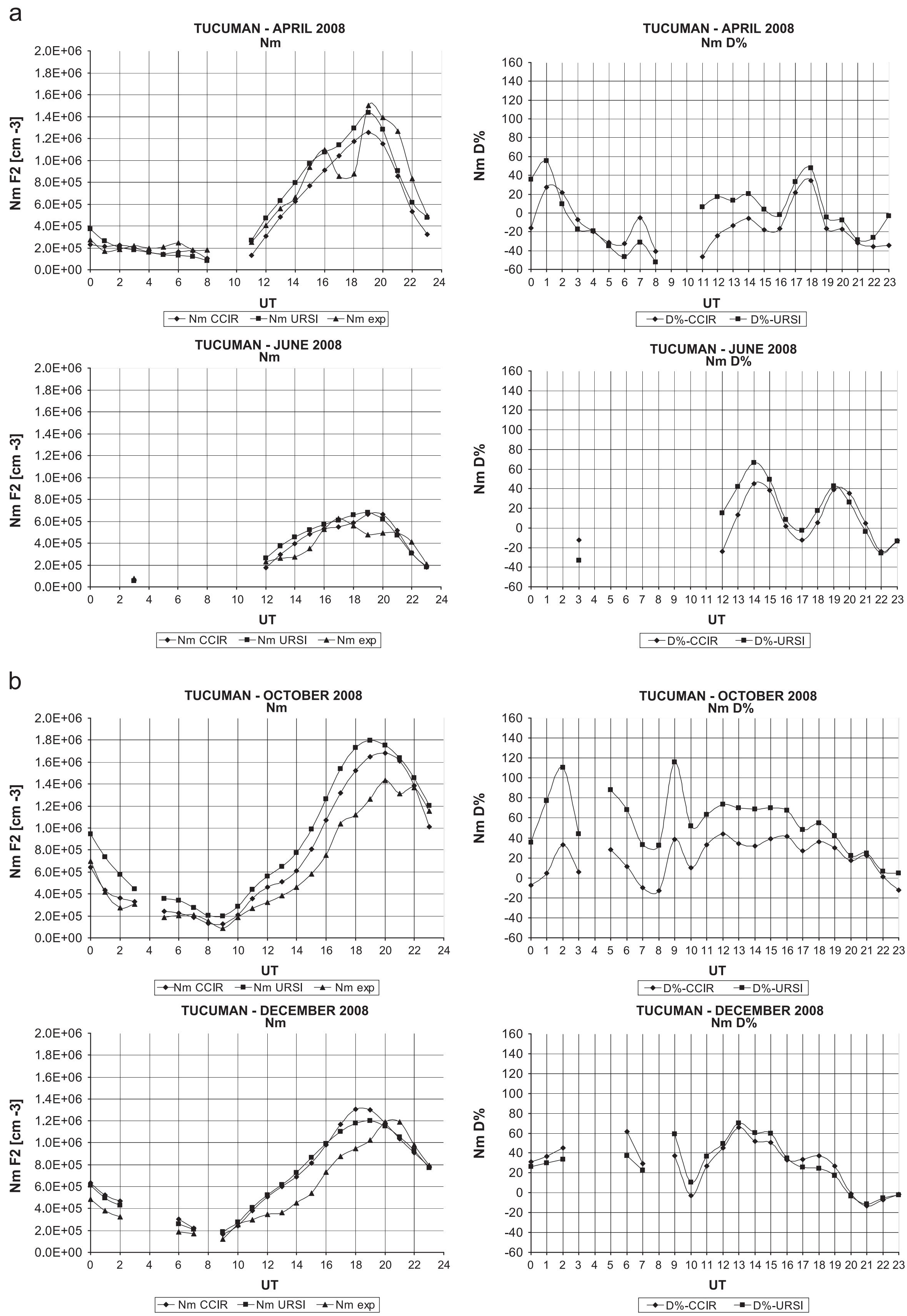

Fig. 6. (a) Modeled and experimental NmF2 values and corresponding deviations for April and June, 2008. 16 UT = 12 LT, (b). Modeled and experimental NmF2 values and corresponding deviations for October, and December 2008. 16 UT = 12 LT.

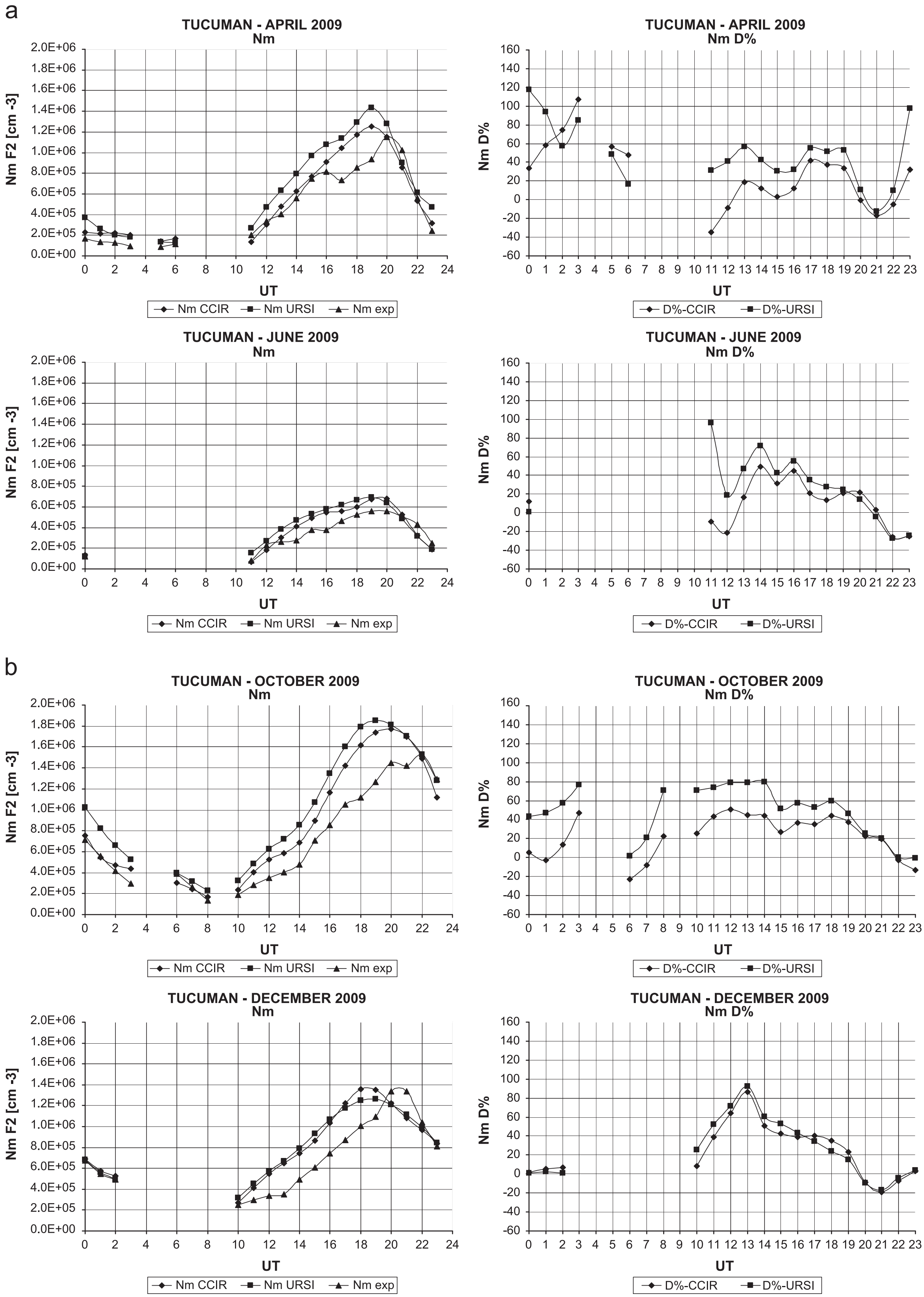

Fig. 7. (a) Modeled and experimental NmF2 values and corresponding deviations for April and June, 2009 16 UT = 12 LT, (b). Modeled and experimental NmF2 values and corresponding deviations for October, and December 2009. 16 UT = 12 LT.

expected result due to the low solar activity. (e) The semmianual anomaly which is present in the behaviour of foF2 at times of increased solar activity was not clearly observed during the period 2008–2009. This phenomenon could be related with the very low solar activity for that period, confirming the relationship of the amplitude of this anomaly with the solar activity reported by other authors. (f) In most cases, the values of hmF2 recorded in the deep solar minimum are lower than those observed in the period 1975–1976, suggesting a decrease in the height of the ionosphere in the course of time, which could be related to the greenhouse effect in the atmosphere and the anomalously low solar extreme-ultraviolet irradiance. (g) IRI predictions of NmF2 show significant deviations from the experimental values, indicating the need for improvements in the model.

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