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F2 region maximum electron density height predictions for South American latitudes

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[1] Values of the F2 region maximum electron density height (hmF2) calculated using ground ionosonde data at South American latitudes are used to check the validity of the International Reference Ionosphere (IRI) to predict this variable. With this in mind we compare hmF2 predictions given by the model when measurements of critical frequency of F2 region and propagation parameter M(3000)F2 were used as input parameter in IRI ($hmF2_{IRI\text{-}Exp}$), against those obtained using the standard International Radio Consultative Committee (CCIR) option ($hmF2_{IRI\text{-}CCIR}$). In this paper we used $hmF2_{IRI\text{-}Exp}$ values because hmF2 measurements were not available for the considered cases. Moreover, a comparison of the measured M(3000)F2 values with the CCIR predictions have been done. The results show that, in general, the standard predictions follow the diurnal tendency observed in the $hmF2_{IRI\text{-}Exp}$ values. At low latitudes the $hmF2_{IRI\text{-}Exp}$ values show oscillations not reproduced by the standard option. Cases with disagreements for 24 hours have been observed at high latitudes. Other cases with good agreement have been also obtained. The results suggest that, in general, the standard option of the model gives good hmF2 predictions at South American latitudes. Few cases showed deviation between 15 and 25%. As we expected, the obtained results suggest that the deviation between predicted and measured M(3000)F2 values is the main contribution for the deviation between $hmF2_{IRI\text{-}CCIR}$ and $hmF2_{IRI\text{-}Exp}$. The comparison with the results obtained in previous work shows that the IRI performance in predicting M(3000)F2 and hmF2 is better than in predicting foF2. *INDEX TERMS:* 2447 Ionosphere: Modeling and forecasting; 2415 Ionosphere: Equatorial ionosphere; 2443 Ionosphere: Midlatitude ionosphere; 2467 Ionosphere: Plasma temperature and density; *KEYWORDS:* electron density, ionosphere, peak height

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1. Introduction

[2] For successful radio communication, it is essential to predict the behavior 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. This need for prediction leads to modeling of the ionosphere. Several physical, empirical and semiempirical models [e.g., *Anderson*, 1973; *Barghausen et al.*, 1969; *Bent et al.*, 1976; *Llewellyn and Bent*, 1973; *Bilitza*, 1990; *Anderson et al.*, 1987] have been developed to predict ionospheric variables.

[3] In a previous work, *Ezquer et al.* [1996] used measurements of the critical frequencies of the ionospheric regions (f_oE, f_oF1 and f_oF2) obtained at South American stations for different solar conditions and seasons to check the validity of the International Reference Ionosphere (IRI) model [*Bilitza*, 1990] to predict these frequencies. They found good predictions for f_oE and f_oF1 when compared. The degree of accuracy among experimental and predicted f_oF2 values was lower than those observed for the other frequencies, which is well known and is due to higher variability in the F2 region, and cases with strong disagreements were observed by *Ezquer et al.* [1996].

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Table 1. Considered Stations

	Geodetic Coordinates
Huancayo	(−12.05, 284.67)
Tucumán	(−26.90, 294.60)
Bs. Aires	(−34.55, 301.30)
Port Stanley	(−51.70, 302.20)
Ushuaia	(−54.80, 291.70)
Islas Argentinas	(−65.20, 295.70)

[4] In order to complete the study of *Ezquer et al.* [1996], in the present paper values of the F2 region maximum electron density height (hmF2) calculated using data of f_oF2 and M(3000)F2 obtained at South American latitudes are used to check the validity of the International Reference Ionosphere to predict this variable. Taking into account that for this study hmF2 measurements were not available, we compare hmF2 predictions given by the model when measurements of critical frequency of F2 region and propagation parameter M(3000)F2 were used as input parameter in IRI ($hmF2_{IRI\text{-}Exp}$), against those obtained using the standard CCIR option ($hmF2_{IRI\text{-}CCIR}$). In the IRI model f_oE measurements cannot be used as an input coefficient. Only cases with 24 hours measurements were considered.

2. IRI Model

[5] The Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI) established an international task group to develop and improve a standard model of the ionospheric plasma parameter. This model is the International Reference Ionosphere (IRI) [*Rawer et al.*, 1981; *Bilitza*, 1986; *Rawer and Bilitza*, 1989, 1990; *Bilitza*, 1990]. COSPAR is interested in a general description of the ionosphere as part of the terrestrial environment for the evaluation of environmental effects on spacecraft and experiments in space. The main interest of URSI is the electron density part of IRI for defining the background ionosphere for radiowave propagation studies and applications.

[6] IRI is one of the most widely used empirical models, and has undergone several years of critical checking and improving by the international science community. The emphasis of IRI is to summarize a large collection of ground-based and spacecraft data to provide true height profiles of the ionosphere. IRI gives the altitude dependence of electron density, electron and ion temperatures and the composition of positive iones. For the worldwide description of the peak electron density, the *International Radio Consultative Committee* (*CCIR*) [1967a, 1967b] numerical maps are used as a choice. In this work we are interested in the F2 peak height.

[7] In the IRI model, hmF2 is obtained by its close correlation with the propagation parameter M(3000)F2 [*Shimazaki*, 1955; *Bradley and Dudeney*, 1973; *Bilitza et al.*, 1979]. M(3000)F2 is defined as

$$M(3000)F2 = MUF/f_oF2, \qquad (1)$$

where MUF is the maximum usable frequency that, refracted in the ionosphere, can be received at a distance of 3000 km. This factor has been routinely scaled from ionograms, and numerical maps [*CCIR*, 1967a, 1967b] are used has a choice in the model. The F2 peak height is calculated from M(3000)F2 with the empirical formula [*Bilitza et al.*, 1979]

$$hmF2 = 1490/[M(3000)F2 + DM] - 176 \qquad (2)$$

with the correction factor

$$DM = f_1 f_2/(f_oF2/f_oE - f_3) + f_4 \qquad (3)$$

and the solar activity functions

$$f_1 = 0.00232\ R_{12} + 0.222 \qquad (4)$$

$$f_2 = 1 - R_{12}/150\ \exp\left(-(\Psi/40)^2\right) \qquad (5)$$

$$f_3 = 1.2 - 0.0116\ \exp(R_{12}/41.84) \qquad (6)$$

$$f_4 = 0.096(R_{12} - 25)/150. \qquad (7)$$

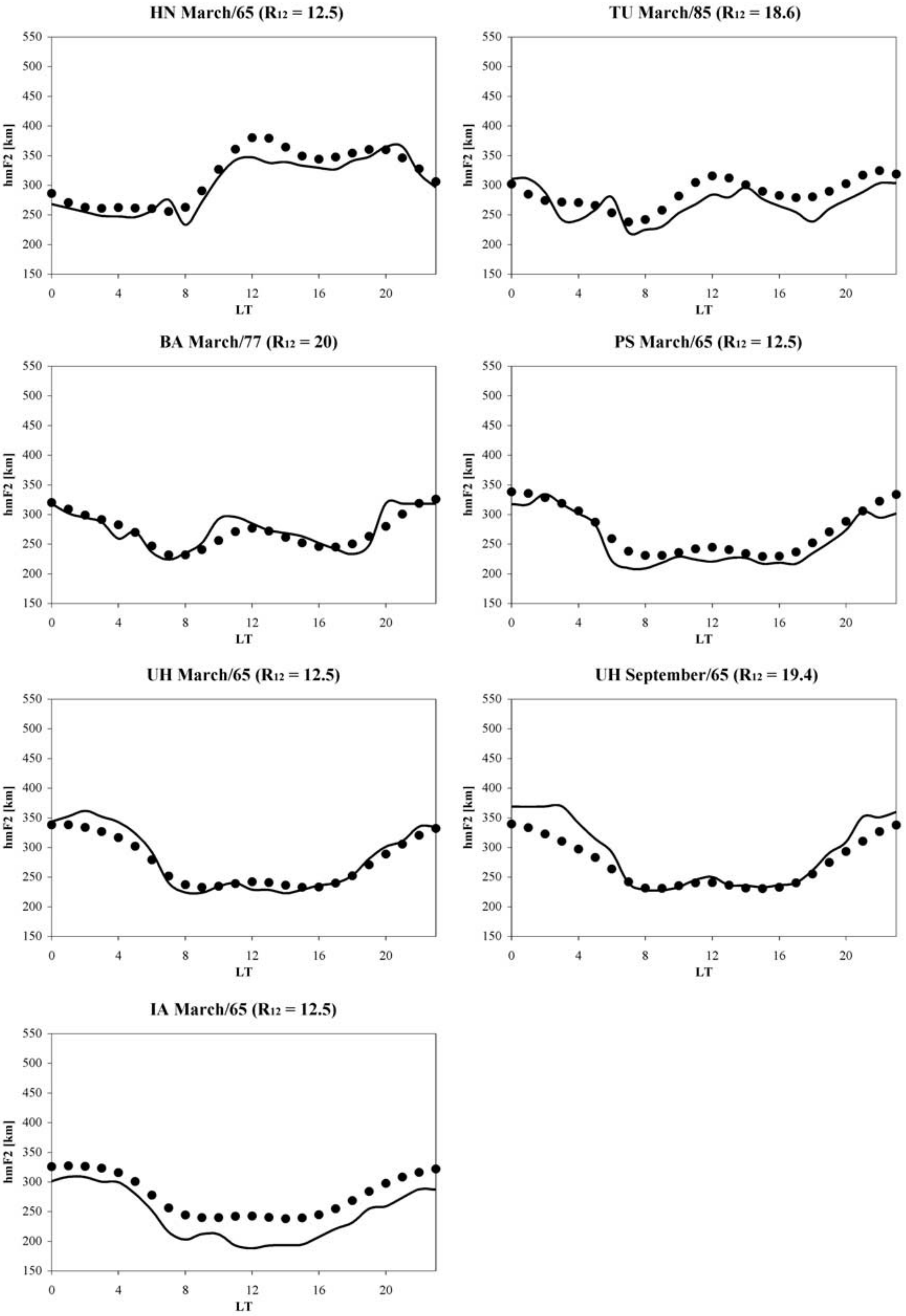
R_{12} is the 12-month-running mean of solar sunspot number, and Ψ is the magnetic dip latitude

$$\tan\Psi = 1/2\ \tan\psi \qquad (8)$$

which is related to the magnetic inclination (short: dip) ψ of the Earth's magnetic field at 300 km altitude.

[8] In this paper we calculate hmF2 using the CCIR options in IRI and also using ground ionosonde measurements as input parameters in the model, from now on: $hmF2_{IRI\text{-}CCIR}$ and $hmF2_{IRI\text{-}Exp}$ values, respectively. For this purpose, the internet online version of IRI (IRI 95), (http://nssdc.gsfc.nasa.gov/space/model/models/iri.html), has been used. We assume that $hmF2_{IRI\text{-}Exp}$ is a more

Figure 1. (opposite) The $hmF2_{IRI\text{-}Exp}$ (solid line) and $hmF2_{IRI\text{-}CCIR}$ (circles) values for Huancayo (HN), Tucumán (TU), Buenos Aires (BA), Port Stanley (PS), Ushuaia (UH) and Islas Argentinas (IA). Equinox, low solar activity.


HN March/65 (R_{12} = 12.5)
TU March/85 (R_{12} = 18.6)
BA March/77 (R_{12} = 20)
PS March/65 (R_{12} = 12.5)
UH March/65 (R_{12} = 12.5)
UH September/65 (R_{12} = 19.4)
IA March/65 (R_{12} = 12.5)
hmF2 [km]
550
500
450
400
350
300
250
200
150
0
4
8
12
16
20
LT

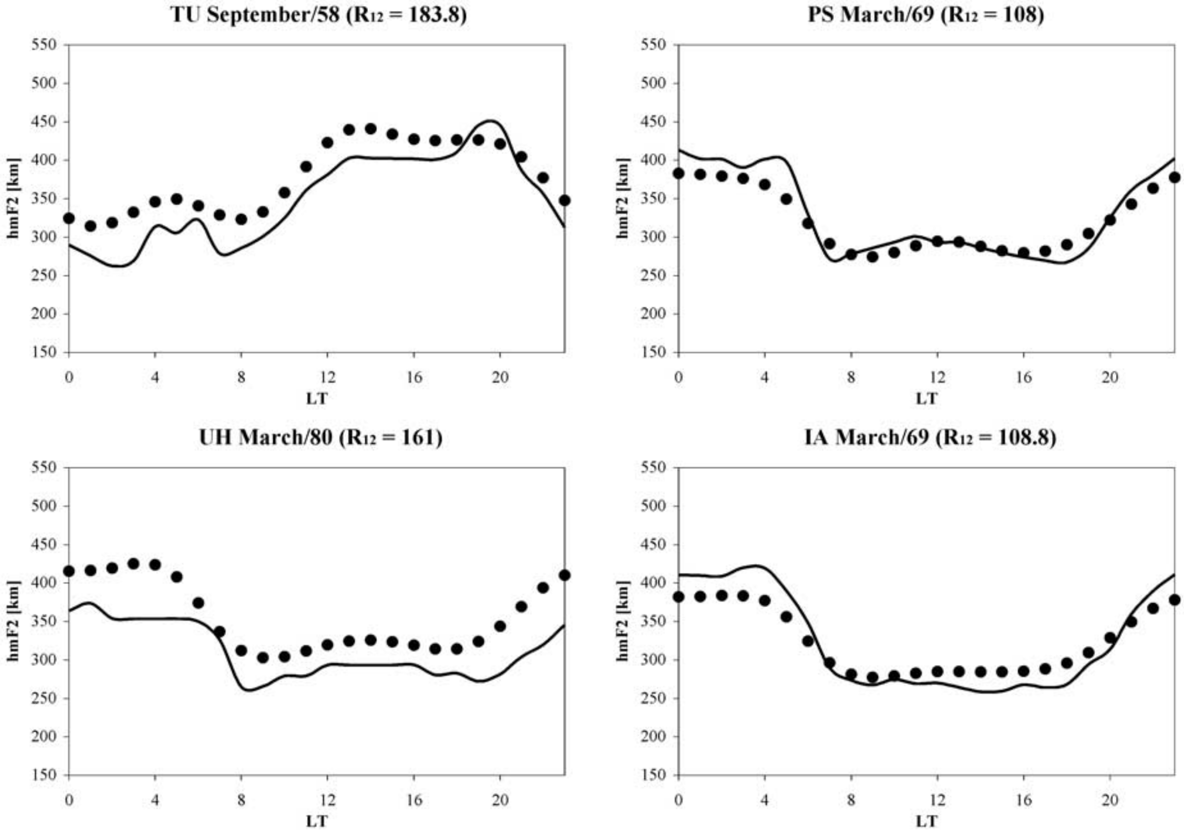


Figure 2. The $hmF2_{IRI-Exp}$ (solid line) and $hmF2_{IRI-CCIR}$ (circles) values for Tucumán (TU), Port Stanley (PS), Ushuaia (UH) and Islas Argentinas (IA). Equinox, high solar activity.

realistic value of the maximum electron density height. The use of the URSI model is beyond the scope of the paper.

3. Data

[9] Hourly monthly median values of M(3000)F2 and f_oF2 measured at the stations listed in Table 1 were used to calculate hmF2. We consider equinoxes and solstices for years of low (1965, 1977, 1985) and high (1958, 1969, 1980) solar activities. Only typical results are shown in this paper.

[10] It is well know that the ionosphere produces several effects on transionospheric radio waves. These effects are proportional to the number of free electrons encountered by the wave on its passage through the ionosphere (total electron content, TEC). The highest TEC values in the world occur in the near-equatorial region. This region extends approximately 20° either side of the magnetic equator, with the highest value not at the equator, but rather at the so-called "equatorial anomaly (EA) peaks region" at approximately ±15° from the magnetic equator. Tucumán is placed near the southern peak of the EA. *Ezquer et al.* [1995, 1998] showed that the IRI model underestimated TEC measured above Tucumán. Their results suggest that the ionization contribution from the equator, which causes the EA, affects the ionosphere over Tucumán producing an electron density profile broader than those assumed by the model.

4. Results and Discussion

[11] Figure 1 shows the results for equinox and low solar activity. It can be seen that the IRI-CCIR predictions follow the tendency of the curve obtained with measured M(3000)F2 factor ($M(3000)F2_{Exp}$), at all stations. At low latitudes, $hmF2_{IRI-CCIR}$ is greater than $hmF2_{IRI-Exp}$ during daytime conditions and does not reproduce the oscillations shown by $hmF2_{IRI-Exp}$. The best agreement is observed at Ushuaia daytime hours. For Islas Argentinas, $hmF2_{IRI-CCIR}$ is greater than $hmF2_{IRI-Exp}$ for all hours of the day. The disagreement observed at Tucumán could be produce by the influence of the EA on the Tucumán's ionosphere which is not well

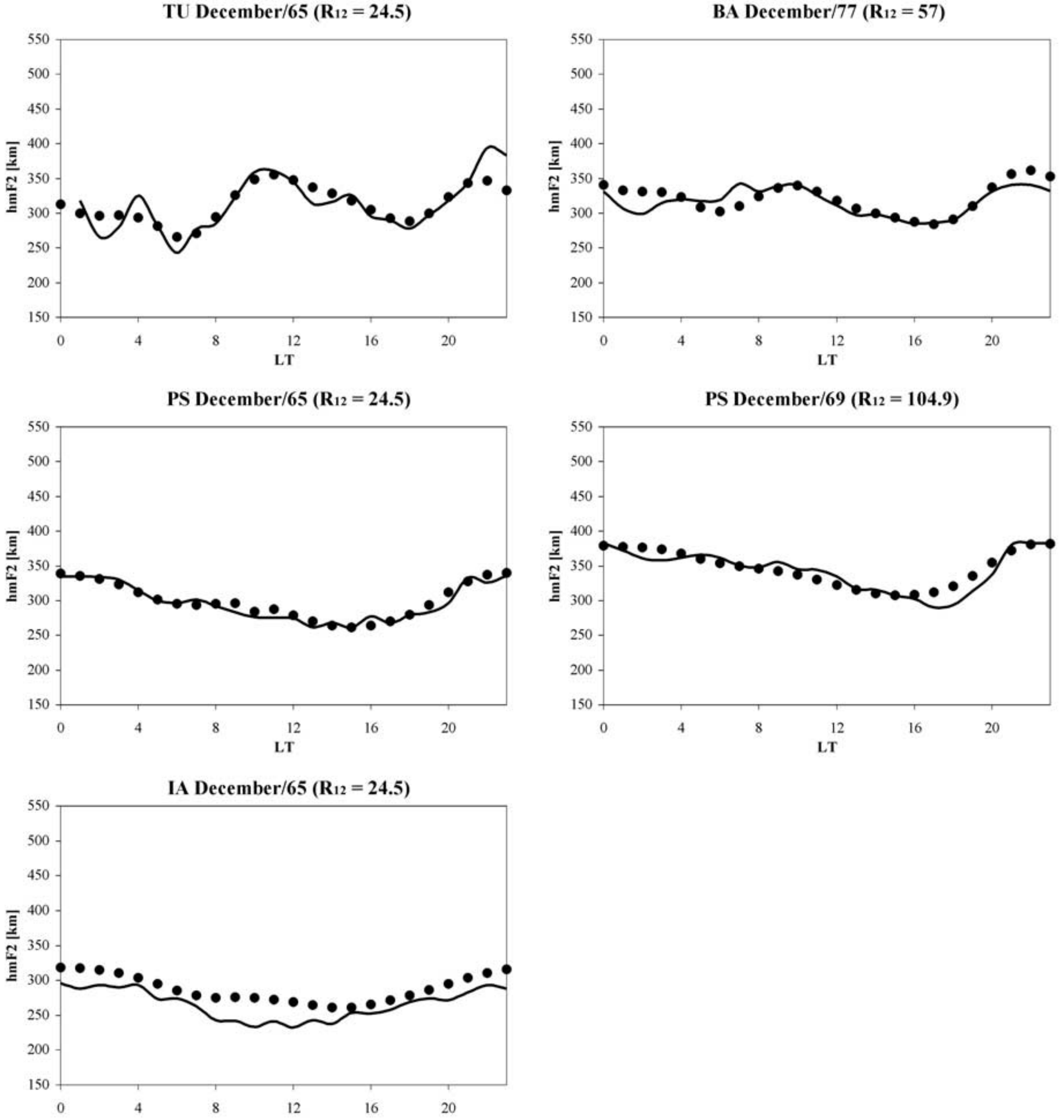


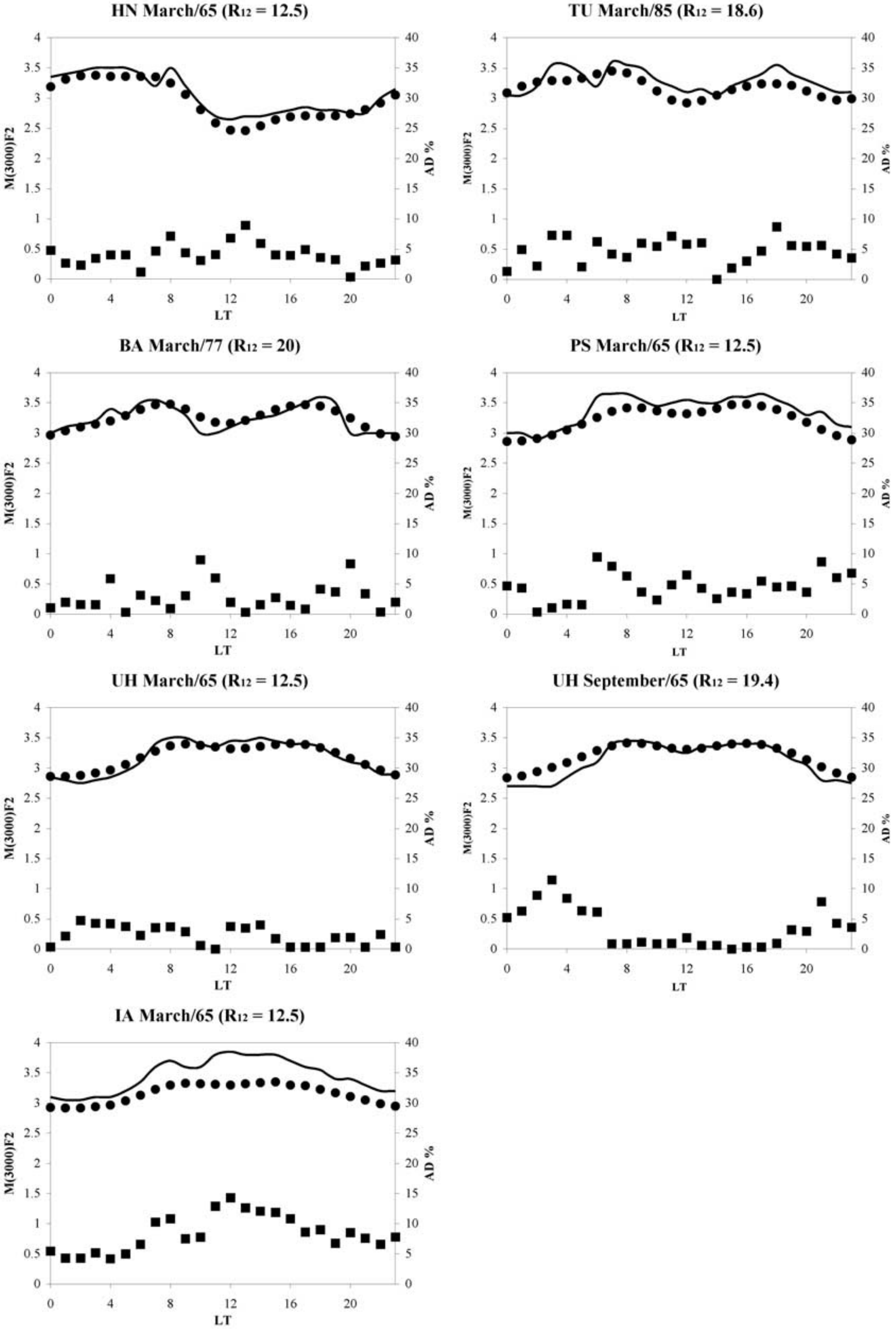
Figure 3. The $hmF2_{IRI\text{-}Exp}$ (solid line) and $hmF2_{IRI\text{-}CCIR}$ (circles) values for Tucumán (TU), Buenos Aires (BA), Port Stanley (PS) and Islas Argentinas (IA). Solstices.

reproduced by the model; and that observed at Islas Argentinas could be produced because Islas Argentinas latitude is close to the validity model boundary [*Bilitza*, 1990].

[12] The results for equinox, high solar activity, are shown in Figure 2. At Tucumán, $hmF2_{IRI\text{-}CCIR}$ exceeds $hmF2_{IRI\text{-}Exp}$ from 0 LT to 17 LT. This situation is observed for almost all the day at Ushuaia. The best agreement between both curves is obtained for Port Stanley during daytime conditions.

[13] Figure 3 shows the results for solstices considering different solar conditions. The best agreement between both curves is observed for Port Stanley.

[14] Taking into account that the calculated hmF2 depends on M(3000)F2 factor, as is shown in equation (2), a comparison among measured and predicted M(3000)F2



HN March/65 (R_{12} = 12.5)

TU March/85 (R_{12} = 18.6)

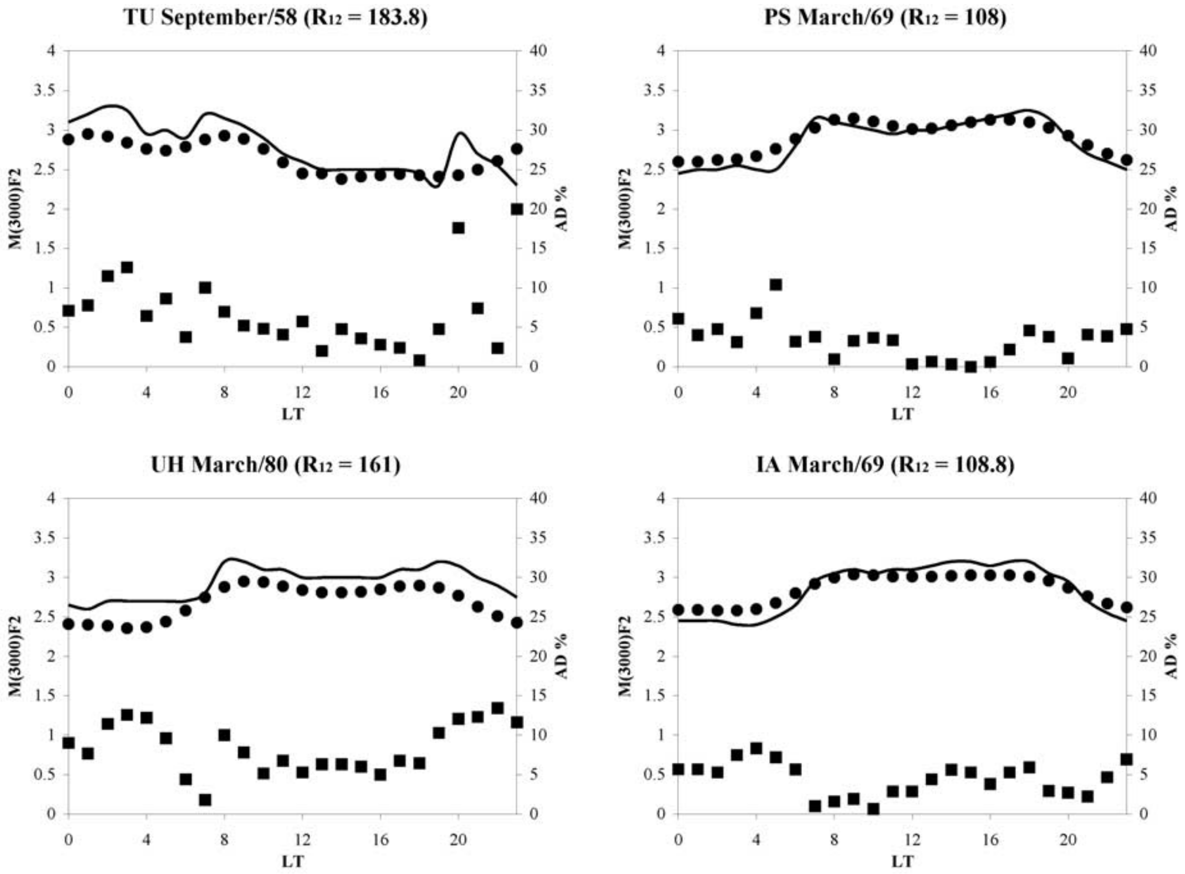
BA March/77 (R_{12} = 20)

PS March/65 (R_{12} = 12.5)

UH March/65 (R_{12} = 12.5)

UH September/65 (R_{12} = 19.4)

IA March/65 (R_{12} = 12.5)


TU September/58 (R12 = 183.8)

PS March/69 (R12 = 108)

UH March/80 (R12 = 161)

IA March/69 (R12 = 108.8)

Figure 5. The M3000F2$_{Exp}$ (solid line) and M3000F2$_{CCIR}$ (circles) values for Tucumán (TU), Port Stanley (PS), Ushuaia (UH) and Islas Argentinas (IA). Equinox, high solar activity. Absolute deviations in percent of M3000F2$_{Exp}$ (squares).

has been done. Figures 4, 5 and 6 show the results for the cases considered in Figures 1, 2, and 3, respectively. An opposite behavior to that observed for hmF2 can be seen. In these figures we included the absolute value of the deviation between prediction and measurement in percentage of measurement, calculated as:

$$AD = \left[\left|\left(M(3000)F2_{CCIR} - M(3000)F2_{Exp}\right)\right| / M(3000)F2_{Exp}\right] * 100. \tag{9}$$

It can be seen that for few cases AD is greater than 10%.

[15] For the used ionosondes, the error when foF2 is measured is about 0.1 MHz, and the average error for the M(3000)F2 factor measurements is about 2%, which is lower than the AD observed in the considered cases.

[16] In order to check the incidence of M(3000)F2 disagreements on the deviation between hmF2$_{IRI\text{-}CCIR}$ and hmF2$_{IRI\text{-}Exp}$, we calculated the following deviations:

$$Dev = \left[\left(hmF2_{IRI-CCIR} - hmF2_{IRI-Exp}\right) / hmF2_{IRI-Exp}\right] * 100 \tag{10}$$

$$Dev = \left[\left(M(3000)F2_{CCIR} - M(3000)F2_{Exp}\right) / M(3000)F2_{Exp}\right] * 100. \tag{11}$$

Figure 4. (opposite) The M3000F2$_{Exp}$ (solid line) and M3000F2$_{CCIR}$ (circles) values for Huancayo (HN), Tucumán (TU), Buenos Aires (BA), Port Stanley (PS), Ushuaia (UH) and Islas Argentinas (IA). Equinox, low solar activity. Absolute deviations in percent of M3000F2$_{Exp}$ (squares).

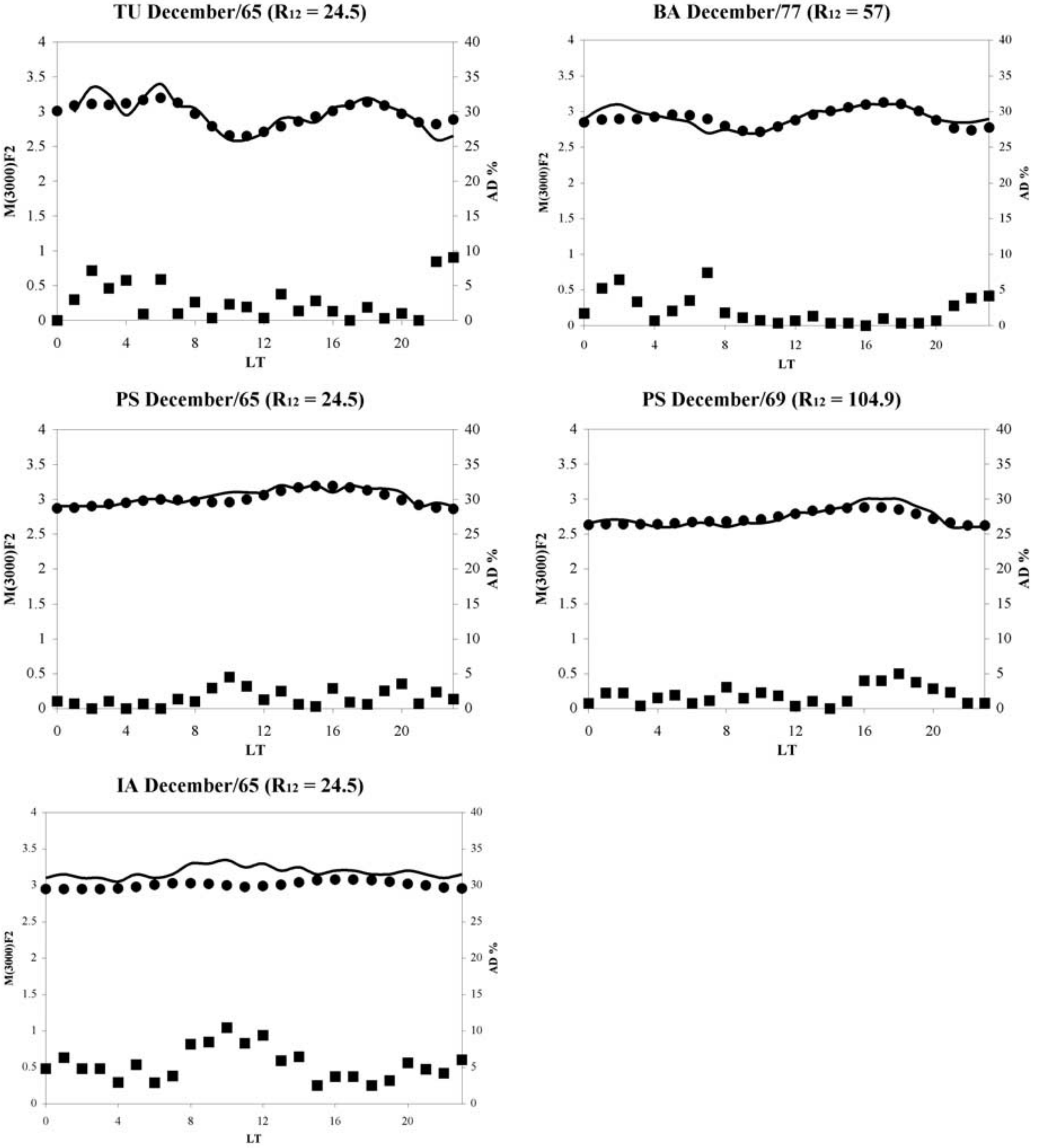
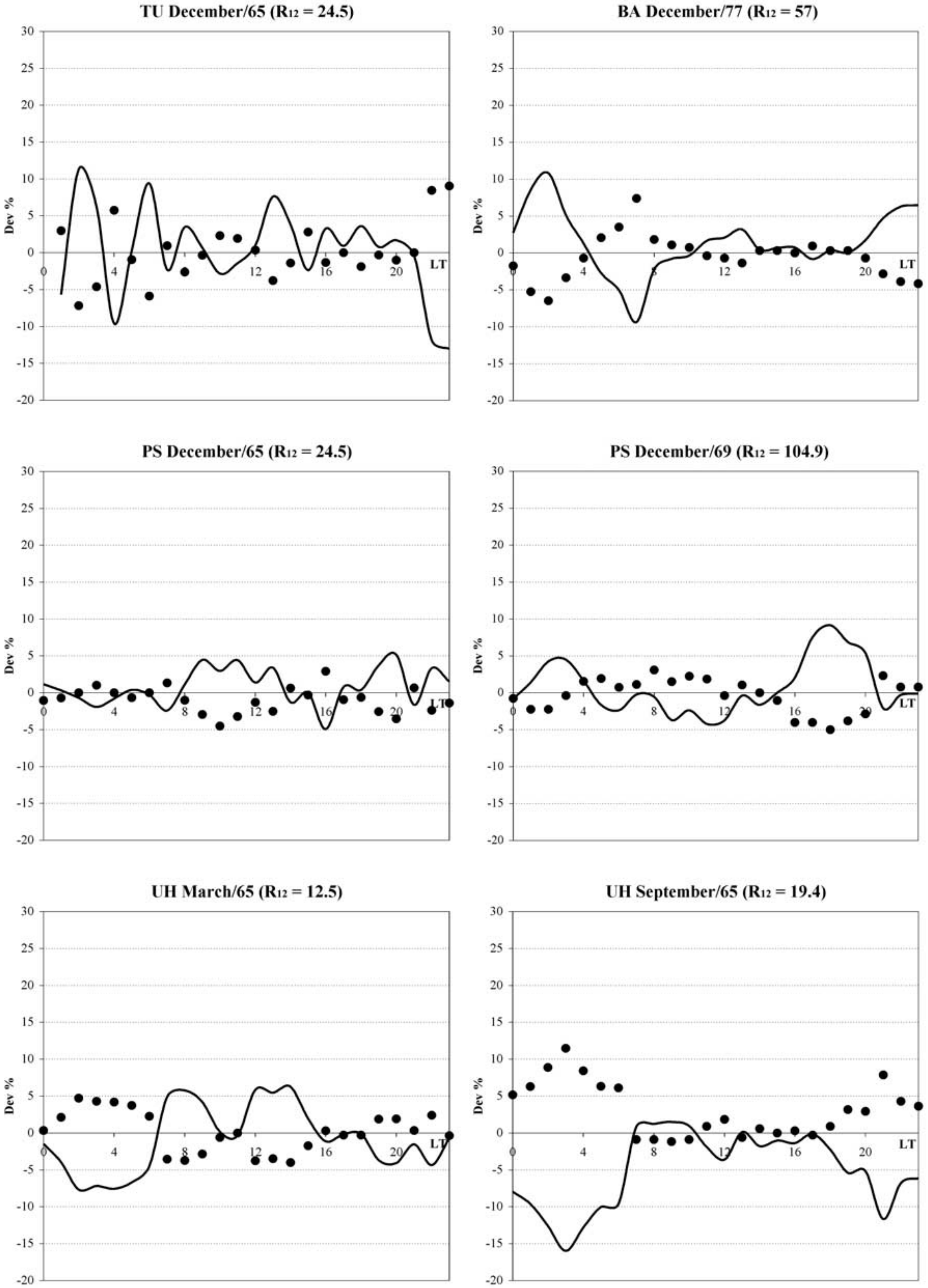


Figure 6. The M3000F2$_{Exp}$ (solid line) and M3000F2$_{CCIR}$ (circles) values for Tucumán (TU), Buenos Aires (BA), Port Stanley (PS) and Islas Argentinas (IA). Solstices. Absolute deviations in percent of M3000F2$_{Exp}$ (squares).

Figure 7. (opposite) Deviations between hmF2$_{IRI\text{-}Exp}$ and hmF2$_{IRI\text{-}CCIR}$, in percent of hmF2$_{IRI\text{-}Exp}$ (solid line), for Tucumán (TU), Buenos Aires (BA), Port Stanley (PS) and Ushuaia (UH). Cases with hmF2 deviations lower than 15%. M(3000)F2 deviations in percent of M(3000)F2$_{Exp}$ (circles).


TU December/65 (R12 = 24.5)
BA December/77 (R12 = 57)
PS December/65 (R12 = 24.5)
PS December/69 (R12 = 104.9)
UH March/65 (R12 = 12.5)
UH September/65 (R12 = 19.4)
Dev %
LT
30
25
20
15
10
5
0
-5
-10
-15
-20
0
4
8
12
16
20

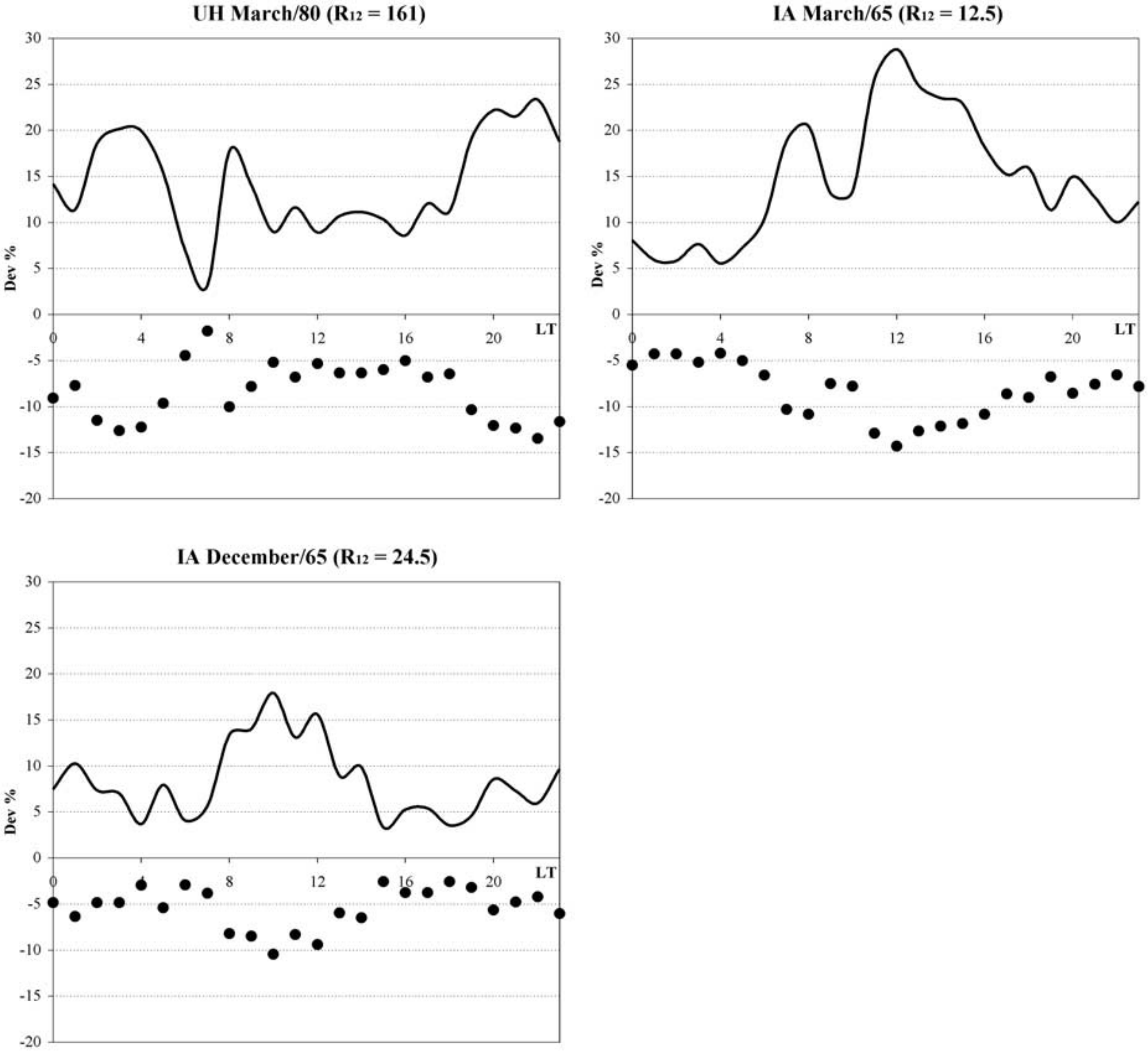


Figure 8. Deviations between $hmF2_{IRI-Exp}$ and $hmF2_{IRI-CCIR}$, in percent of $hmF2_{IRI-Exp}$ (solid line), for Ushuaia (UH) and Islas Argentinas (IA). Cases with hmF2 deviations lower than 30%. M(3000)F2 deviations in percent of $M(3000)F2_{Exp}$ (circles).

Figure 7 presents cases with hmF2 deviations lower than 15%. Both curves show an almost symmetrical behavior suggesting that, as expected, the main contribution to the hmF2 deviation is that observed for M(3000)F2 factor.

[17] Figure 8 shows the highest observed deviations, which correspond to high latitude. hmF2 and M(3000)F2 deviations show similar behavior to that observed at Figure 7. Moreover, it can be seen that the obtained values of hmF2 deviations are not greater than 30%.

[18] *Ezquer et al.* [1996] showed that for South American stations, the maximum deviation of the predicted f_oF2 values from the measurements could reach values as high as 50% or more. Those results suggested that it would be possible to plan a HF circuit with a predicted frequency, which is greater than the maximum frequency that the circuit can support. Assuming that $hmF2_{IRI-Exp}$ is a more realistic value of the F2 region maximum electron density height, we can say that the deviation values obtained in the present paper, in general, are lower than those obtained previously for f_oF2. These results suggest that the model performance in predicting M(3000)F2 factor and hmF2

is better than in predicting f_oF2 for South American stations.

5. Conclusions

[19] In order to complete a previous work on ionospheric predictions for South American latitudes, in the present paper a study to check the validity of IRI model to predict hmF2 has been done. The results show that, in general, the standard predictions follow the diurnal tendency observed in $hmF2_{IRI-Exp}$ values. At high latitudes cases with disagreement for 24 hours have been observed. However, other cases with good agreement have also been obtained.

[20] The deviation between $hmF2_{IRI-CCIR}$ and $hmF2_{IRI-Exp}$, in general, are lower than 15%. Few cases, corresponding to high latitudes, showed disagreements between 15 and 25%. An important contribution to hmF2 deviation is the deviation between $M(3000)F2_{CCIR}$ and $M(3000)F2_{Exp}$. The comparison with the results obtained by *Ezquer et al.* [1996] shows that the IRI performance in predicting M(3000)F2 and hmF2 is better than in predicting f_oF2.

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