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The variability of foF2 in different phases of solar cycle 23

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ABSTRACT

In this paper we examined the variations of the foF2 with solar activity for different local time and different seasons. Beside this we evaluated International Reference Ionosphere (IRI) models at different phases of solar cycle 23, different latitudes and different local time. We studied F2 layer critical frequency (foF2) of the ionosphere by using the flare index calculated by the Kandilli Observatory. For this purpose, we identified the months similar with high flare activity during the solar cycle 23. We chose 6 months which represented the different phases (ascending branch, maximum and descending branch) of the solar cycle. We also took into account the fact that these months were in different seasons. The hourly monthly means of observed foF2 data from four ionosonde stations for 6 months were calculated. On the other hand, the identical foF2 values of the same months were calculated for the year 1996, which is the minimum year of the previous solar activity cycle. We subtracted the foF2 values of 1996 from the values of the selected months of the last solar cycle to obtain the residuals, Δ(foF2). Then the magnitude of the residuals is compared through the cycle. We used IRI-2007 as well as IRI-2001 models to see the degree of deviation of the observed results from the predicted ones. We found that the predicted values of the ΔfoF2, which are calculated by the IRI-2007, fitted well with the observed Δ(foF2) and showed that the Δ(foF2) are dependent on the solar cycle variations in general.

1. Introduction

The ionosphere, the layer of the Earth's atmosphere that extends from 80 to 1000 km, can significantly affect the propagation of radio waves. Many communication systems utilize the ionosphere to reflect radio signals over long distances. The ionosphere may act as an efficient reflector with frequencies below about 30 MHz, allowing high frequency (HF) radio communication to distances of many thousands of kilometers. In HF radio propagation, the critical frequency (foF2) is the limiting frequency at or below which a radio wave is reflected by and the wave penetrates through an ionospheric F-layer if it is above this value. On the other hand, this layer of the ionosphere is subject to a number of influences such as solar ionizing radiation, solar wind, geomagnetic activity, neutral atmosphere and electrodynamics' effects (Rishbeth and Mendillo, 2001). The spatial scales of inhomogeneties cause turbulence varying from thousands of kilometers to scale sizes of less than a meter. In the same way, the temporal scales change in a range of many years (solar cycle effects on ionospheric propagation) to hours or even minutes (Cannon et al., 2004).

Ionospheric variability has been examined by various authors (Tulunay, 1995; Forbes et al., 2000; Wilkinson, 2004; Batista and Abdu, 2004; Oyeyemi et al., 2006; Bencze, 2007; Sethi et al., 2008; Rios et al., 2007; Adeneyi et al., 2007; Chuo and Lee, 2008). The characteristics of the F2 region of the ionosphere must be accurately predicted especially during the periods of high solar activity. This is an important factor for HF communications. Therefore, considerable efforts have been put on modeling the ionospheric parameters. Several models are described by community coordinated modeling center internet site (http://ccmc.gsfc.nasa.gov/modelweb/ionos/about_ionos.html). The International Reference Ionosphere (IRI) is an empirical standard model of the ionosphere sponsored by the Committee on Space Research (COSPAR) and International Union on Radio Science (URSI). The IRI has many practical applications in HF predictions. This model can give an average value of foF2 taking into consideration the effect of the time of the day, seasons, solar cycle and the coordinates of the ionospheric station around the world surface. The most recent IRI model (IRI-2007), which describes the electron density in the altitude range from about 50 to about 2000 km (Bilitza, 2001) is available on internet. It is important to revise this model periodically to improve its prediction capability.

In order to help these efforts, it is beneficial to compare the observed ionospheric parameters with the predicted ones during the different phases of solar cycles. In this study, our aim is to calculate the difference between the measured hourly values of

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foF2 over four ionospheric stations during the previous minimum and different phases of solar cycle. We have shown how the magnitude of this difference has changed during the solar cycle 23. Besides this, we have calculated the predicted hourly foF2 values by using the ionospheric model IRI-2007 for the same months and stations. The predicted magnitude of the difference from the model was determined and was compared with the observed one. The main purpose of this paper is to investigate the dependence of the foF2 variability on solar activity over different latitudes, different local times, different seasons and comparison with IRI-2007 model.

2. Data and analysis

Continuous solar observations are required to catch short-lived, infrequent phenomena. One important example is solar flares. Images of the Sun show that solar flares are one of the most powerful and explosive forms of the solar activity. Many studies in space weather field classify solar flares as one of the most important solar events affecting the Earth's environment. Solar flares produce sudden large amounts of X-rays and extreme ultraviolet (EUV) energy. This energy from the Sun affects the Earth's ionosphere that becomes suddenly more ionized, thus changing the densities and location of ionospheric layers. The solar activity indices used in this study are given as follows:

Flare index: It was introduced by Kleczek (1952). The relationship "$FI = it$" quantifies the daily flare activity over a 24-h period. In this relation, i represent the intensity scale of importance of a flare in H_α and t the duration of the flare in minutes. He assumed that this relationship roughly gave the total energy emitted by the flare and named it 'flare index' (FI). Catalogues of flare activity using Kleczek's method are given for each day from 1936 to 2006 by Kleczek (1952), Knoska and Petrasek (1984), Ataç (1987) and Ataç and Özgüç (1976–2006, ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/INDEX/).

Mg II core-to-wing index: The Mg II core-to-wing ratio is derived by taking the ratio of the h and k lines of the solar Mg II feature at 280 and 282 nm. The h and k lines are variable chromospheric emissions while the background emissions are more stable. The result is a robust measure of chromospheric activity. This ratio has been shown to be a good measure of the chromospheric activity. We used the daily NOAA Mg II index to show how the high flare activity enhances the solar ultraviolet (UV) and extreme ultraviolet (EUV) emissions since the solar radiation in the UV and EUV wavelengths is responsible for the photoionization of the Earth's upper atmosphere.

The ionospheric data is obtained through the prompt ionospheric database of the UK solar system data center and the Space Physics Interactive Data Resource, SPIDR. The observed foF2 values were used from the four ionospheric stations within the period 1996–2006. We computed the predicted foF2 values for the mentioned period by using the ionosphere model of IRI-2007 (http://ccmc.gsfc.nasa.gov/modelweb/models/iri.html) for comparing purposes.

In Fig. 1 we plotted the monthly flare index and monthly mean of the Ap index. If the value of the daily flare index once exceeded 40 during a month we assumed that this month is rich with flare activity. We identified 19 months with high flare index between the years 1996 and 2006; 4 of these months are on the ascending branch (1996–1999), 7 months at the maximum (2000–2001) and 8 months are on the descending branch (2002–2006) of the solar cycle 23. We selected 6 similar months among these which represented the different phases (ascending branch, maximum and descending branch) of the solar cycle. We also took into account the fact that these months are in different seasons (Table 1). The variations of the solar and geomagnetic activities during these selected months can be seen in Figs. 1–3. We show the geomagnetic activity variations during these selected months by using Dst, Kp indices; and for the solar activity FI and MgII indices. The geomagnetic activity of all selected months is higher than the cycle average, except July 2002, even though this month has high flare activity (Table 1).

In this paper, we made an attempt to show the variations of the foF2 during the different levels of solar activity over mid-latitude stations from the European sector (Juliusruh, 54.6°N, 13.4°E, Rome 41.8°N, 12.5°E, Sofia, 42.7°N, 23.4°E) and a low-latitude station (Learmonth, 21.9°S, 114°E) from the Australian sector. First we

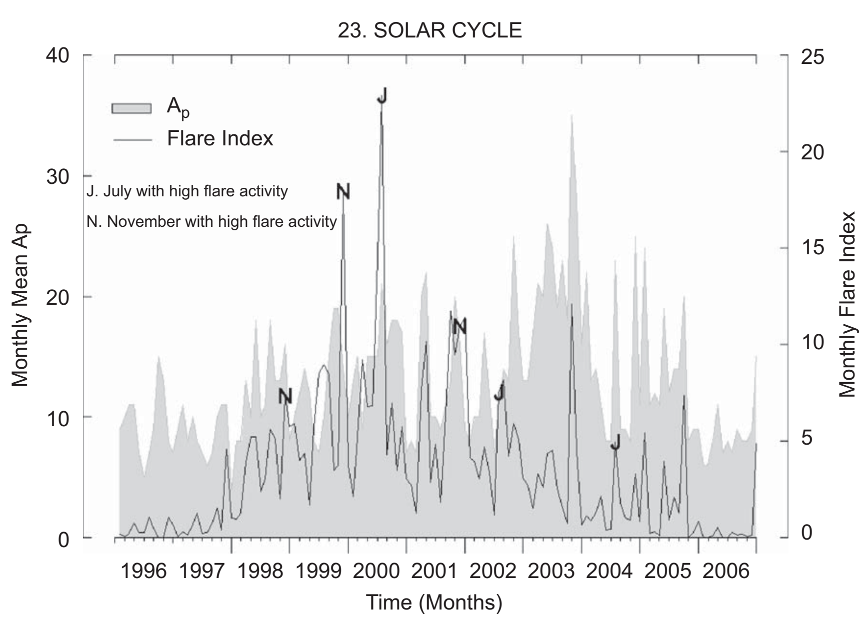

Fig. 1. The variations of the monthly flare index and monthly planetary magnetic activity index Ap. The selected months July and November, which represent the different levels of solar activity, are shown by capital letters J and N.

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calculated the observed monthly means of the hourly values of foF2 for the selected months and for the same month of the solar minimum in 1996. Then we subtracted the mean hourly foF2 values of the 1996 from the selected month's values:

$$\Delta(\mathrm{foF_2})_{\mathrm{Observed}} = (\mathrm{foF_2})_{\mathrm{Ob-year}} - (\mathrm{foF2})_{\mathrm{Ob-1996}}$$

This gives us the magnitude of the difference in MHz during the different levels of the solar activity and also helps us to see how residual hourly foF2 are different for different seasons in various locations. Values are chosen from the months of November and July of different years to emphasize different seasons.

We calculated the predicted hourly values of foF2 for our selected months by using IRI-2007 as well as IRI-2001 models. For the predicted values we followed the same procedure as we did to calculate the observed ΔfoF2. Then we obtained the magnitude of the predicted difference between the minimum year 1996 and the different solar activity periods of solar cycle 23:

$$\Delta(\mathrm{foF2})_{\mathrm{Predicted}} = (\mathrm{foF2})_{\mathrm{Pr-year}} - (\mathrm{foF2})_{\mathrm{Pr-1996}}$$

The variations of the magnitude of these differences between the minimum and selected periods of the solar activity during the selected months of July and November are shown in Figs. 4 and 5. We show how the observed ΔfoF2 deviate with the predicted ones by calculating their root mean square deviations. The results are given in Tables 2 and 3. As it can be seen from these tables, the observed ΔfoF2 are in better agreement with the predicted results of the IRI-2007 model than the values of the previous version of the IRI model. This can be expected since Bilitza and Reinisch (2008) in their very recent paper describe the various improvements, which are added to the latest version of the IRI-2007 model.

Table 1
Selected similar months during the different part of solar cycle 23 with high flare and geomagnetic activity.

Selected months	Cyc. mean$_{(1996–2006)}$: 12.8 A_p mean	Cyc. mean$_{(1996–2006)}$: 3.5 FI mean	23 cycle/phase
July 2000	21	23.0	Maximum
July 2002	11	7.5	Descending branch
July 2004	23	5.0	Descending branch
November 1998	16	7.4	Ascending branch
November 1999	14	18.0	Ascending branch
November 2001	16	11.0	Maximum

3. Results and discussion

Solar radiation in the UV and EUV wavelengths is responsible for the photoionization of the ionosphere. The electromagnetic radiation and especially energetic particles from the Sun vary always. Strong solar flares and associated particle events can occur at different phases of solar cycle: rising, declining and even at solar minimum. The solar maximum is distinguished by higher occurrence frequency of those events. However, the fluxes of energetic particles of galactic and magnetospheric origin vary also with solar cycle. Though under quiet and moderately disturbed geomagnetic conditions, their impact to the dayside ionosphere is minor in comparison with the solar radiation. Moreover, fluxes of galactic cosmic rays anticorrelate with the solar activity. In contrast, the magnetospheric particles play important role in perturbations of whole ionosphere during magnetic storms. Therefore, we identified 19 months with high flare activity and

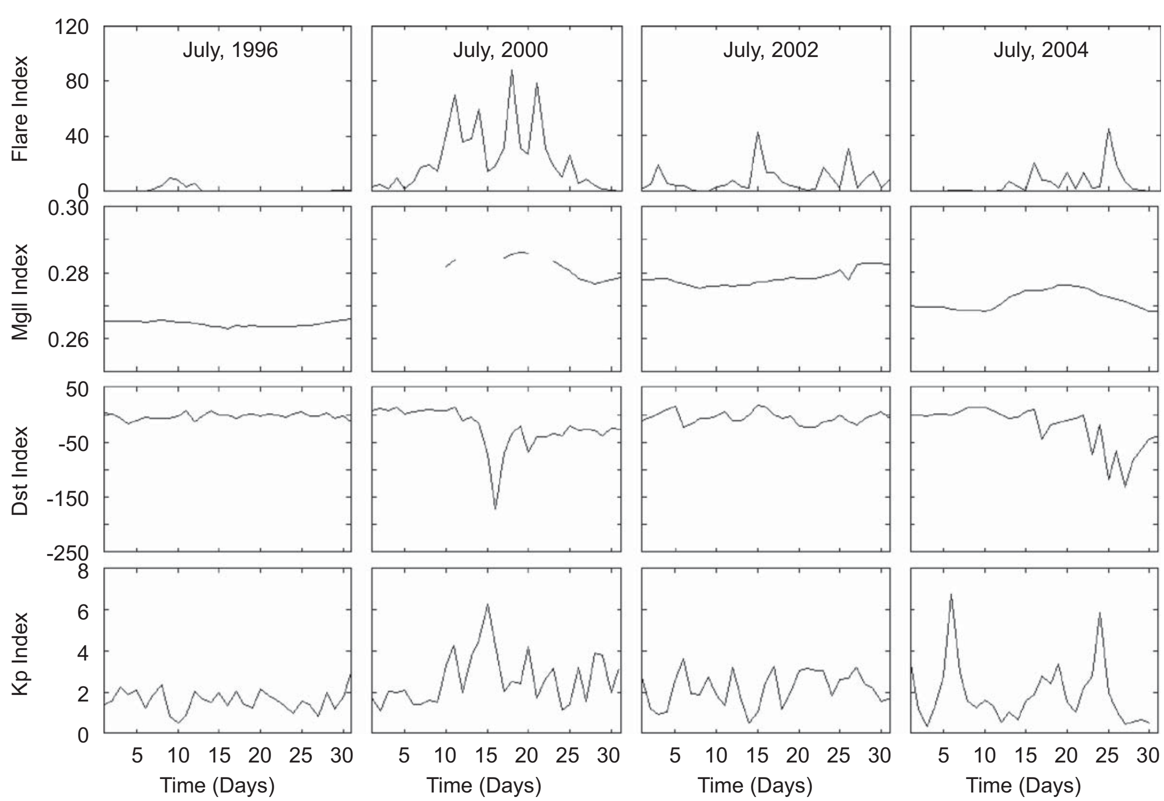

Fig. 2. The monthly variations of the flare, Mg II and the geomagnetic (Dst, Kp) indices during the months July for 4 years.

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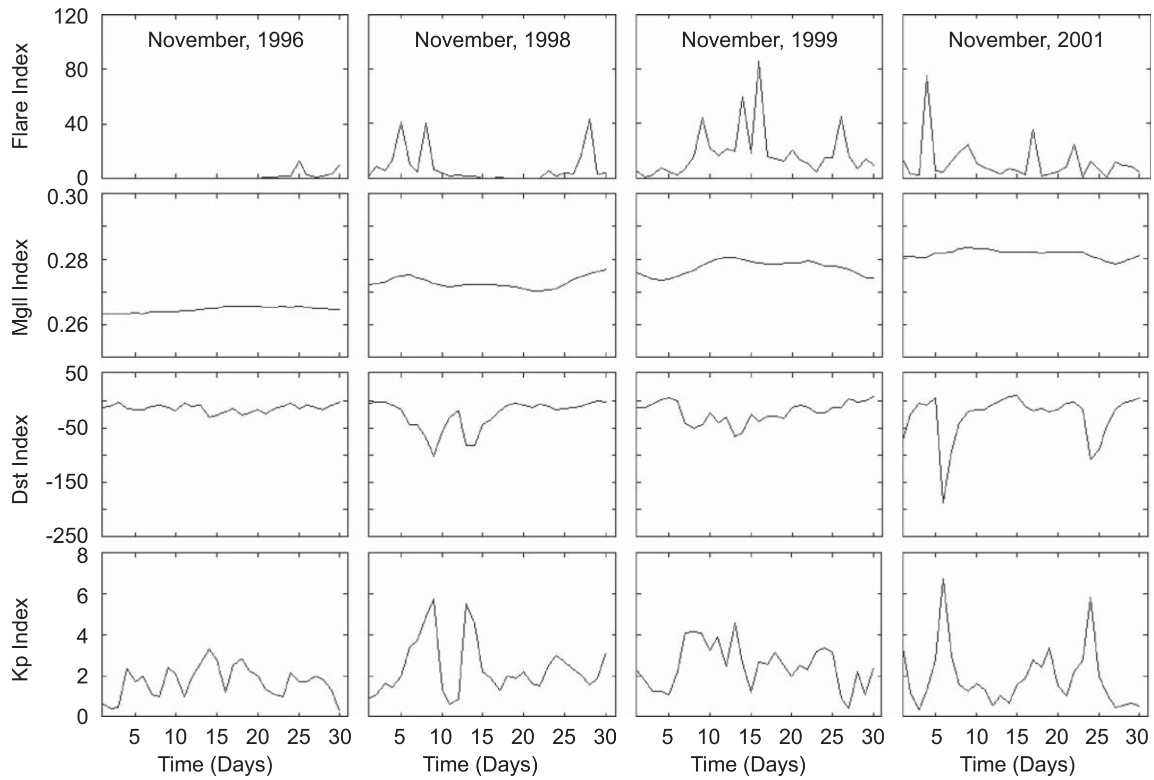

Fig. 3. The monthly variations of the flare, Mg II and the geomagnetic (Dst, Kp) indices during the months November for 4 years.

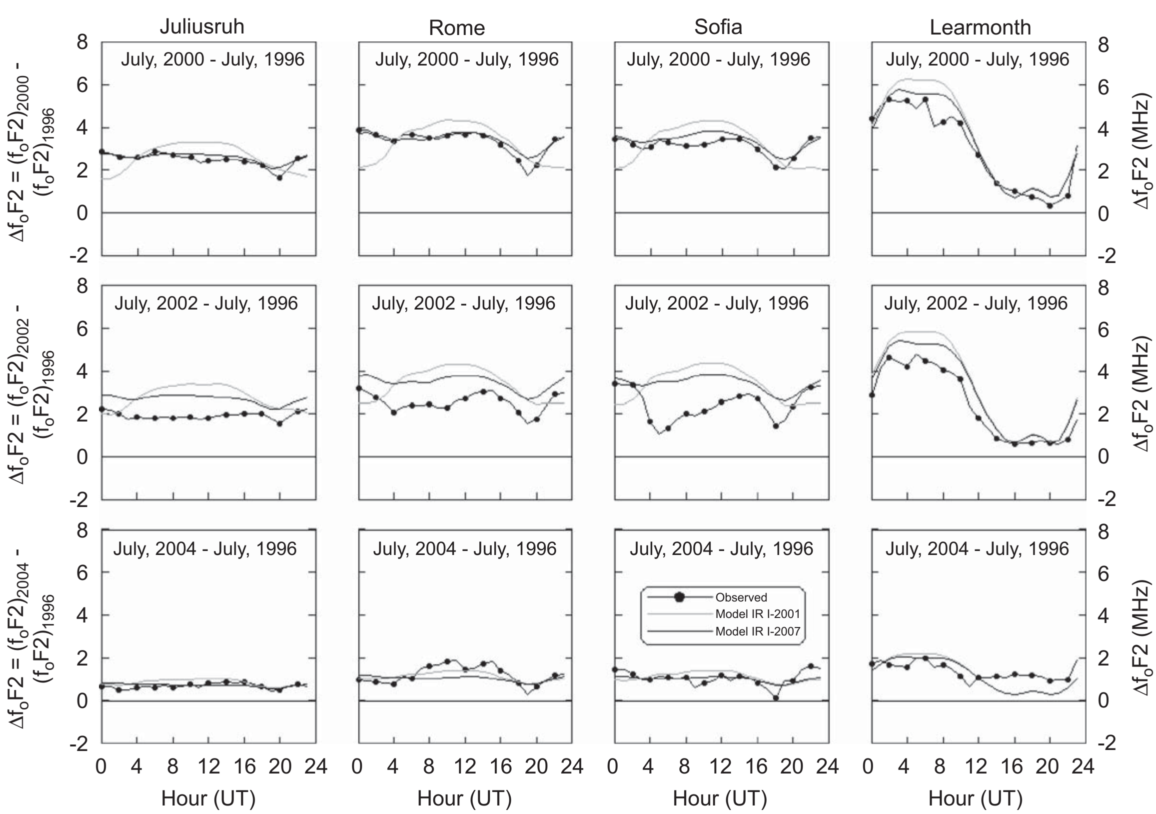

Fig. 4. The magnitude variations of the ΔfoF2 for the studied stations for the selected Julys during the different levels of solar activity. The dotted lines represent the observed ΔfoF2, the thick lines IRI-2007 and the thin lines IRI-2001.

most of these months are on the maximum and on the descending branch of the solar cycle 23. We especially selected 6 similar months with high flare activity on different parts of the solar cycle which represented the different levels of solar activity. Consequently, electron concentration and critical frequency of F2 region (foF2) are also expected to reflect these variations.

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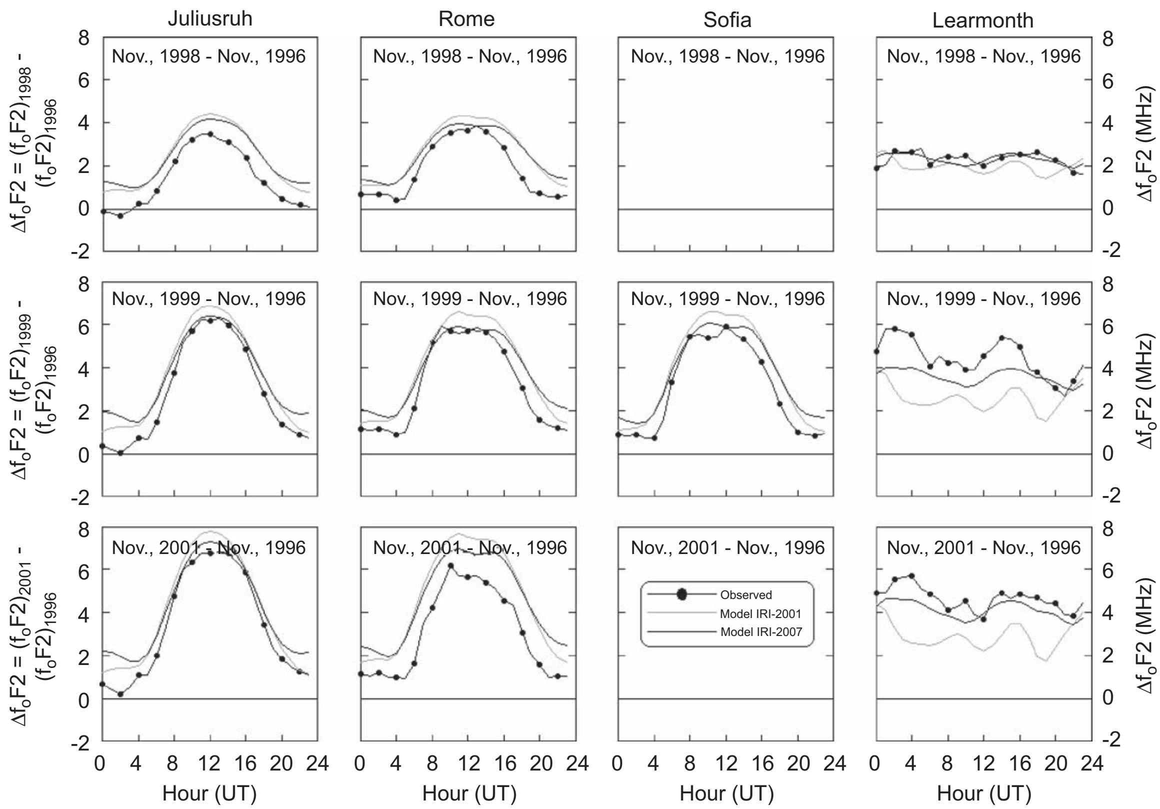

Fig. 5. The magnitude variations of the ΔfoF2 for the studied stations for the selected Novembers during the different levels of solar activity. The dotted lines represent the observed ΔfoF2, the thick lines IRI-2007 and the thin lines IRI-2001.

Table 2
Comparison of the values of the root mean square deviation (RMSD) of the observed and the predicted ΔfoF2 values calculated by IRI-2001 and 2007 models for the studied stations for the selected July months.

RMSD obs./model	ΔfoF2 (MHz) (2000–1996)		ΔfoF2 (MHz) (2002–1996)		ΔfoF2 (MHz) (2004–1996)	
July	IRI-2007	IRI-2001	IRI-2007	IRI-2001	IRI-2007	IRI-2001
JULIUSRUH	0.18	0.66	0.80	1.04	0.14	0.21
ROME	0.23	0.86	0.95	1.16	0.42	0.28
SOFIA	0.31	0.85	1.22	1.55	0.28	0.40
LEARMONTH	0.58	0.84	0.72	0.96	0.55	0.57

Table 3
Comparison of the values of the root mean square deviation (RMSD) of the observed and the predicted ΔfoF2 values calculated by IRI-2001 and 2007 models for the studied stations for the selected November months.

RMSD obs./model	ΔfoF2 (MHz) (1998–1996)		ΔfoF2 (MHz) (1999–1996)		ΔfoF2 (MHz) (2001–1996)	
November	IRI-2007	IRI-2001	IRI-2007	IRI-2001	IRI-2007	IRI-2001
JULIUSRUH	1.00	0.97	0.90	0.77	0.86	0.73
ROME	0.83	0.86	0.85	0.85	1.51	1.64
SOFIA	–	–	0.81	0.88	–	–
LEARMONTH	0.27	0.59	1.07	2.06	0.60	1.90

The results related to the variations of solar activity may be noted as follows:

1. In all cases the variations of the hourly mean of the ΔfoF2 followed the solar cycle variations in general; the magnitude of the ΔfoF2 increases during high solar activity period and decreases during low solar activity period.
2. Around solar activity maximum the magnitude of the ΔfoF2 for the northern hemisphere stations differed significantly for the noontime of July 2000 from November 1999 and 2001 values. This is due to the difference between the noontime and midnight ionospheres of the months July and November.
3. The differences in the magnitude of the variations of the ΔfoF2 between the northern and southern stations are due to the latitude and seasonal effects.

Recently many researchers have compared IRI-2001 predictions and the experimental foF2 observations (Batista and Abdu, 2004;

Chuo and Lee, 2008; Sethi et al., 2008; Rios et al., 2007; Adeneyi et al., 2007). The increasing number of such studies helps to improve the prediction capability of the ionospheric models. The accuracy of the model in a specific region and time period depends on the numbers of the ionospheric stations that are monitoring the ionosphere and adding the new observed ionospheric data to the worldwide network for the specific region and time. IRI predictions are most accurate in northern mid-latitudes because of the high number of the ionosonde stations. The ionosphere shows very high variable conditions at low and high latitudes. This requires more stations, but in both of these regions the widespread of the ionospheric stations are rare. As a result, the IRI predictions are less accurate at equatorial and auroral latitude (Bilitza and Reinisch, 2008).

The complexity of the processes to coupling the atmosphere–ionosphere–magnetosphere makes the physical representation of the ionosphere models difficult. A large number of research group using newer data and with better mathematical descriptions are studying to improve the IRI model. The most important changes in the newest version of the model are about the topside electron density profile, the electron density in the auroral E-region, plasmaspheric electron temperatures, the topside ion composition and the specification of spread probability. In this study, which aimed to contribute to the future improvements of the IRI model, we investigated the variations of the foF2 during the different stages of solar activity over high-mid-latitude stations from European and low-latitude station from Australian sectors. The conclusions can be drawn as follows:

1. The predicted values of the ΔfoF2 calculated by using the model IRI-2007 fitted well when compared with the observed ones as it can be seen from their root mean square deviation in Tables 2 and 3.
2. The predicted values of ΔfoF2 calculated from the model IRI-2007 are found to be systematically higher than the observed values in the northern hemisphere stations.
3. The predicted values of ΔfoF2 calculated from the model IRI-2007 are lower for the months of November but are higher for the months of July in the southern hemisphere station Learmonth. The deviation can be related to the location of Learmonth and to the decrease in electron density during the different seasons.

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