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Predicted and measured bottomside F-region electron density and variability of the D_1 parameter under quiet and disturbed conditions over Europe

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Abstract

Modelling and forecasting of ionospheric parameters is very useful for different radio communication purposes. As long as variations in the ionosphere form regular patterns, the empirical International Reference Ionosphere model, IRI 2000, provides sufficiently accurate corrections to the maximum electron density, N_mF2, to predict the ionospheric effects on radio wave propagation. During geomagnetic storms, however, agreement between the IRI 2000 model and observations is still insufficient. This paper deals with the analysis of measured and model predicted F-region electron densities under quiet and disturbed conditions with the main emphasis placed on the distribution of the F1-region daytime ionisation. Available electron density profiles obtained from ionograms for selected periods from several European ionospheric stations (Pruhonice, Ebro, Arenosillo) were compared with IRI 2000 model results. Comparative analysis shows that discrepancies do exist predominantly during the storm main phase. The model predicted daytime electron densities at the fixed F1-region heights are closer to observed values during summer than winter. Dependences of D_1 on solar activity and season are also analysed.

Keywords: Ionosphere; Geomagnetic storm; Electron density; F1 region; International Reference Ionosphere (IRI)

1. Introduction

The empirical International Reference Ionosphere model, IRI, is being improved and updated continuously after evaluation of new results at the annual workshops and it currently contains a f_oF2 storm model (Araujo-Pradere et al., 2002a, 2002b; Bilitza, 2001, 2003). To assess its predictability, the IRI model is generally checked using measured ionospheric variables such as critical frequencies, heights or electron density profiles. Improvements established by the special Task Force Activity (TFA) team at the International Centre for Theoretical Physics (ICTP) in Italy (since 1995) have been of particular benefit, enabling the IRI to provide a more precise reproduction of the bottomside electron density profile (Radicella et al., 1998; Mosert et al., 2002). The TFA meeting in 1998 adopted a new F1-layer description proposed by Reinisch and Huang (2000), which depends on a single parameter D_1. They analysed the diurnal variation of D_1 for several low latitude station-months. The analysis showed that D_1 behaves systematically, going from zero at sunrise, reaching a maximum at noon, and returning to zero at sunset. The ionosonde

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Table 1
List of the ionospheric stations

Name of the ionospheric station	Geographic latitude and longitude	Magnetic latitude and longitude	Computer code and kind of scaling used for data reprocessing
Pruhonice	50.0°N, 14.6°E	49.7°N, 98.5°E	POLAN (manual scaling)
Ebro	40.8°N, 0.5°E	46.3°N, 80.9°E	ARTIST (automatic scaling)
Arenosillo	37.1°N, 353.2°E	41.4°N, 72.3°E	ARTIST (automatic scaling)

community is now requested to analyse in detail the diurnal behaviour of D_1 as a function of latitude, season and solar activity.

The aim of this study is to compare the diurnal and seasonal behaviour of the bottomside F-region electron density under quiet and disturbed geomagnetic conditions for European middle latitudes, with IRI-predicted electron densities. The new IRI F1-layer parameter D_1 dependencies on the solar activity and season are also analysed using data from Ebro station.

The comparative analysis presented in this paper has been carried out using the IRI 2000 model and ionograms from digital ionosondes, viz., University of Massachusetts Lowell, Centre for Atmospheric Research – DPS systems at Ebro and Arenosillo, and of KEL Aerospace Ltd IPS-42 at Pruhonice. Coordinates of these stations are listed in Table 1. The ARTIST (Huang and Reinisch, 1996 and Reinisch and Huang, 2000) and the POLAN (Titheridge, 1985) computer codes were applied to invert the ionograms to electron density profiles. Electron densities taken from these profiles at F2-region maximum and at fixed F1-region heights were then compared with corresponding IRI values obtained by online computation through the IRI website (http://nssdc.gsfc.nasa.gov/space/model/models/iri.html). We have used the Bo-Tab option (Bilitza et al., 2000) to calculate electron density values below the maximum of the F2 layer. Scotto-97 with the L option was used to obtain the F1 occurrence probability. The f_oF2 STORM model was turned on to

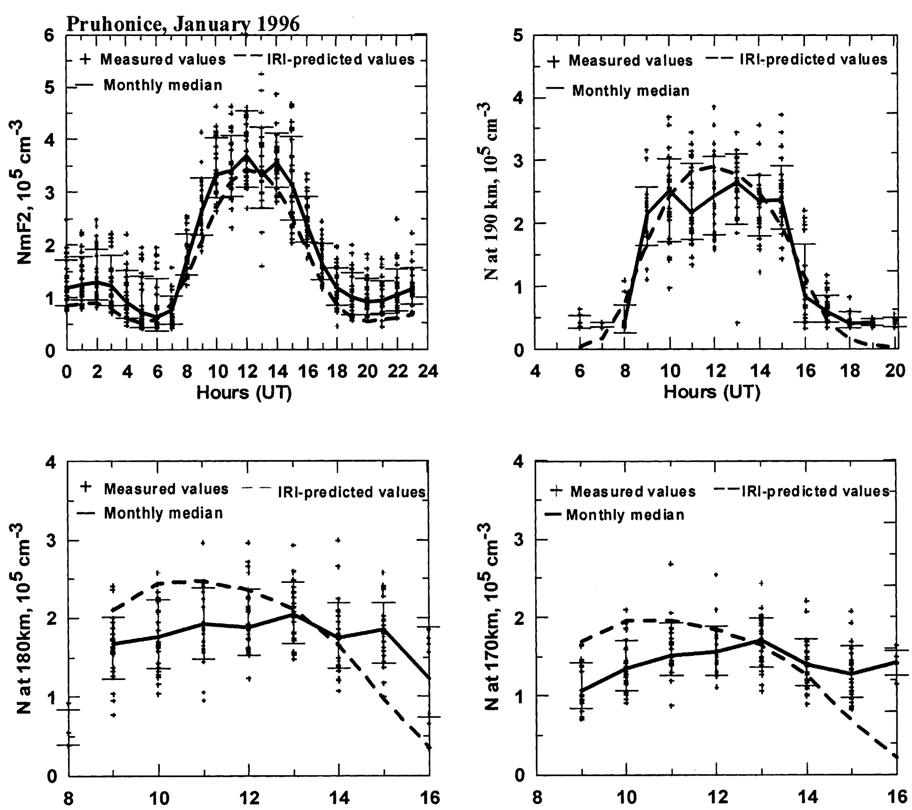

Fig. 1. A scatter plot showing diurnal variation and standard deviation of the electron density values derived from Pruhonice ionosonde in comparison with the electron density predicted by the IRI model for January 1996. (a) for F2-layer peak electron density, (b) for 190 km, (c) for 180 km, (d) for 170 km. The median values are shown as solid lines. The IRI model values are shown as dash lines. Time is in UT.

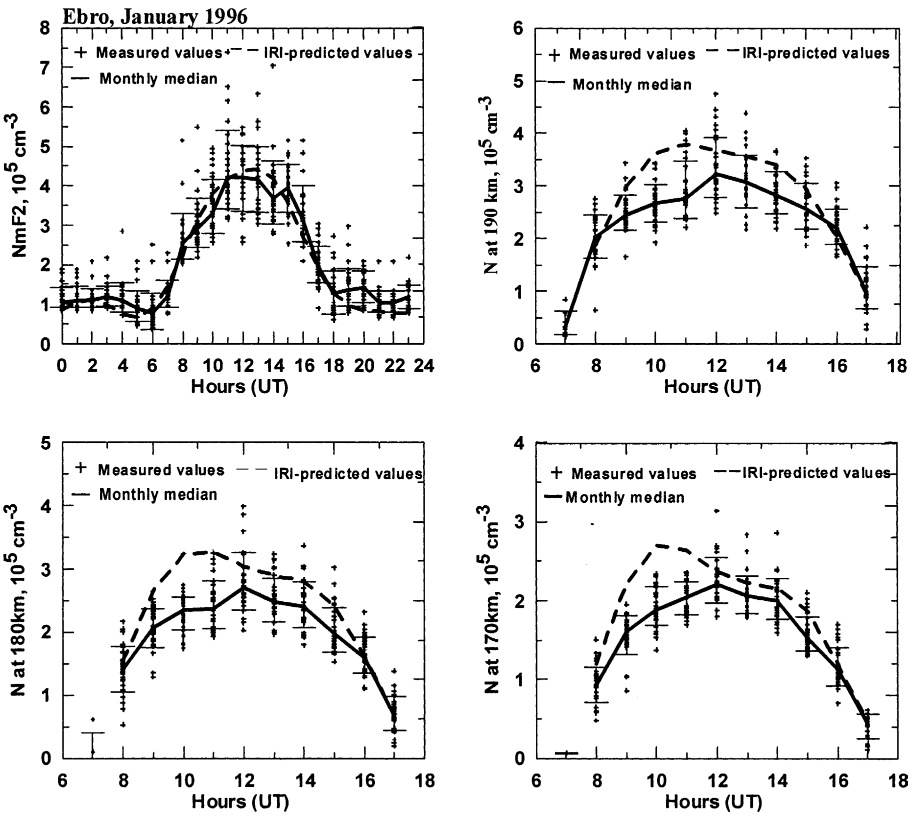

Fig. 2. A scatter plot showing diurnal variation and standard deviation of the electron density values derived from Ebro digital ionosonde in comparison with the electron density predicted by the IRI model for January 1996. (a) for F2-layer peak electron density, (b) for 190, (c) for 180, (d) for 170 km. The median values are shown as solid lines. The IRI model values are shown as dash lines. Time is in UT.

calculate electron density values for the stormy periods analysed.

2. F1 region under storm conditions

During storms, either strong longitudinal and latitudinal asymmetries are observed above two comparable locations, or completely different effects occur in two regions of the ionospheric F2 layer (Prölss, 1995; Buresova and Lastovicka, 2001; Buresova et al., 2002). Moreover, the distribution of storm effects throughout the ionosphere may vary substantially from one event to another. Electron density behaviour has been less explored at F1-region heights than at F2 heights, particularly, during geomagnetic storms. This is partially due to the F1 region being of lower importance for the ionospheric propagation of radio waves. Recently a few papers on the bottomside F-region response to geomagnetic storms have been published. Buresova and Lastovicka (2001) and Buresova et al. (2002) analysed effects of strong geomagnetic storms on the daytime F1-region electron density using data from several European ionosondes. Their results suggested that the F1-region response to geomagnetic storms exhibits systematic seasonal behaviour and depends partly on latitude. Another important finding was that the pattern of the response of the F1 region at European higher middle latitudes, which is a decrease in electron density, does not depend on the type of response of the F2 region or on solar activity. The magnitude of the storm effects usually increases with altitude. At European lower middle latitudes (Ebro, Arenosillo), the geomagnetic storm effects at F1-region heights are less regular. Mikhailov and Schlegel (2003) have reported similar results. They attempted to systematize the geomagnetic storm effects on the F1-region electron density and gave a physical interpretation for the $N(h)$ variations observed using Millstone Hill (middle latitude) and EISCAT (auroral zone) incoherent scatter (IS) daytime measurements.

3. Analysis and results

Initial comparison of the measured and IRI generated $N(h)$ profiles has been carried out for two European ionospheric stations: Pruhonice and Ebro. We have analysed monthly observational and IRI-predicted electron density profiles for January 1996

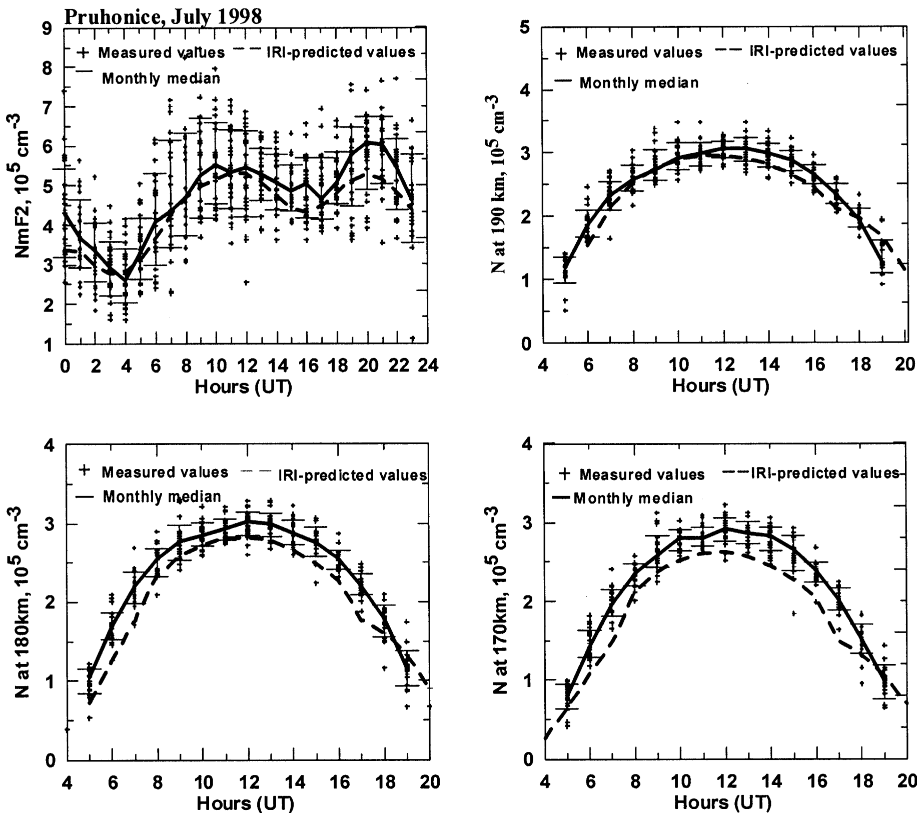

Fig. 3. A scatter plot showing diurnal variation and standard deviation of the electron density values derived from Pruhonice ionosonde in comparison with the electron density predicted by the IRI model for July 1998. (a) for F2-layer peak electron density, (b) for 190 km, (c) for 180 km, (d) for 170 km. The median values are shown as solid lines. The IRI model values are shown as dash lines. Time is in UT.

($Rz12 = 11.5$) and July 1998 ($Rz12 = 66.6$). Geomagnetic activity during both selected months was low (mean A_p of 9 and 11, respectively). Median values for the observations were calculated for hourly intervals. The IRI-predicted median values were obtained for a given $Rz12$ (12-month-running mean sunspot number value). Figs. 1(a)–(d) show the mass plots of N_mF2 as well as the electron density at the selected F1-region heights as a function of universal time (UT) for January 1996, along with the median values and the IRI-predicted values. For Pruhonice the IRI model shows generally good agreement with the N_mF2 observations during daytime (Fig. 1(a)). Slightly greater discrepancies were observed in the late evening and nighttime. The observed and IRI model predicted electron density behaviour at the fixed F1-region heights show disagreements of different magnitudes. At 190 km a few discrepancies occur at about midday while at lower heights, the IRI model values deviate significantly from the observations for the entire period. In the case of Ebro, again, the IRI predictions of the F-region peak density compared well with the observations (Fig. 2(a)) At the F1-region heights of 190, 180 and 170 km (Figs. 2(b), (c) and (d), respectively) we found significant disagreement occurred mainly before noon.

To compare the summer time profiles for the same stations with the IRI model results, corresponding N_mF2- and F1-region electron density values have been plotted in the same way in Figs. 3 and 4 for July 1998. It can be seen from Fig. 3(a) that for Pruhonice the IRI model shows generally good agreement with the F-region peak density observations, except post-noon and in the early morning hours where N_mF2 is underestimated. In contrast to the January 1996 results, the IRI predicted electron density distribution at the F1-region heights is considerably closer to the observations. The IRI slightly underestimates the electron density and the magnitude of this underestimation decreases with altitude. At Ebro station (Fig. 4(a)) it can be seen that, except in the post-noon hours, there is good, agreement between the IRI model and the N_mF2 measurements. In contrast to Pruhonice, the IRI overestimates the F-region peak electron density. A moderate underestimation of the F1-region ionisation has been found starting at about midday (Figs. 4(b)–(c)).

To illustrate the results of the comparative analysis for geomagnetic storms, we have selected four events

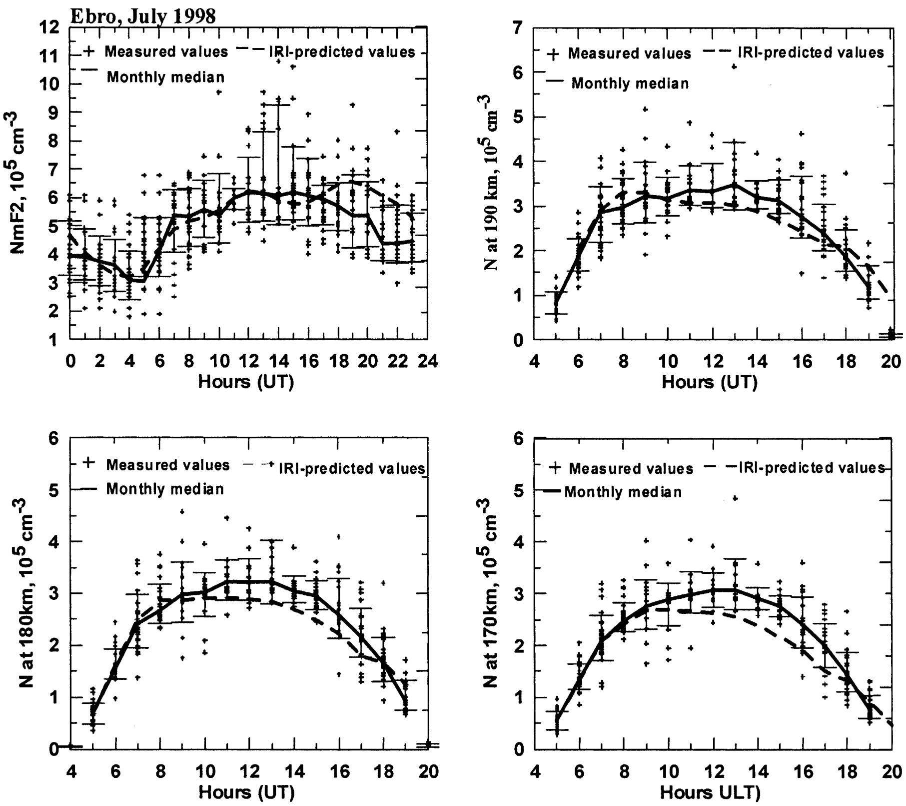

Fig. 4. A scatter plot showing diurnal variation and standard deviation of the electron density values derived from Ebro ionosonde in comparison with the electron density predicted by the IRI model for July 1998. (a) for F2-layer peak electron density, (b) for 190 km, (c) for 180 km, (d) for 170 km. The median values are shown as solid lines. The IRI model values are shown as dash lines. Time is in UT.

Table 2
The analysed geomagnetic storms

Analysed pre-storm and storm period	Storm onset day	Geomagnetic activity indices	*Rz*12	Storm onset hour (UT)	Maximum of the storm (UT)
1998.02.16–22	02/17	$6 < K_p < 7$, A_p 36 min Dst (−103) nT	46.6	13:00	17/22:00
1998.11.11–18	11/13	$6 < K_p < 7$, A_p 60 min Dst (−133) nT	71.9	02:00	13/18:00
2000.07.13–19	07/15	$8 < K_p < 9$, A_p 152 min Dst (−300) nT	119.3	16:00	15/21:00

(Table 2) with, at least one quiet day before the storm onset. These days have been taken as reference days. The effects of three strong geomagnetic storms and super storms on the F-region electron density, and the comparison with the IRI predictions, are presented in Figs. 5–10.

Fig. 5 illustrates the hourly Dst variation and the results for Pruhonice for the February 1998 event. In the analysed period the first day was relatively quiet, followed by the storm, which had its onset on 17 February followed by a long lasting recovery phase. A rather moderate negative storm effect took place during the daytime hours of February 18.

The observed and calculated variations of N_mF2 agree relatively well over the entire analysed period, except for a few deviations during the afternoon hours on 16 and 22 February. The observed decrease in electron concentration at 190 and 180 km for Pruhonice during the storm main phase was much larger than that predicted by the IRI. In general, the IRI overestimated the electron density at F1-region heights, mainly below 190 km. Ebro registered an increase in the F2-layer peak electron density during the storm onset day and significant decrease in N_mF2, as well as in electron density at the fixed F1-region heights, for the next main phase day (Fig. 6). IRI predictions compared well with observations, except for a few discrepancies during the daytime and substantial differences in the daytime electron density behaviour on February 18.

Comparisons of the IRI-2000 predictions with observations for the geomagnetic storm of November 11–18, 1998 are presented in Figs. 7 and 8. The Dst index during the analysed period is plotted in the top panel. Both Pruhonice and Arenosillo recorded a positive storm

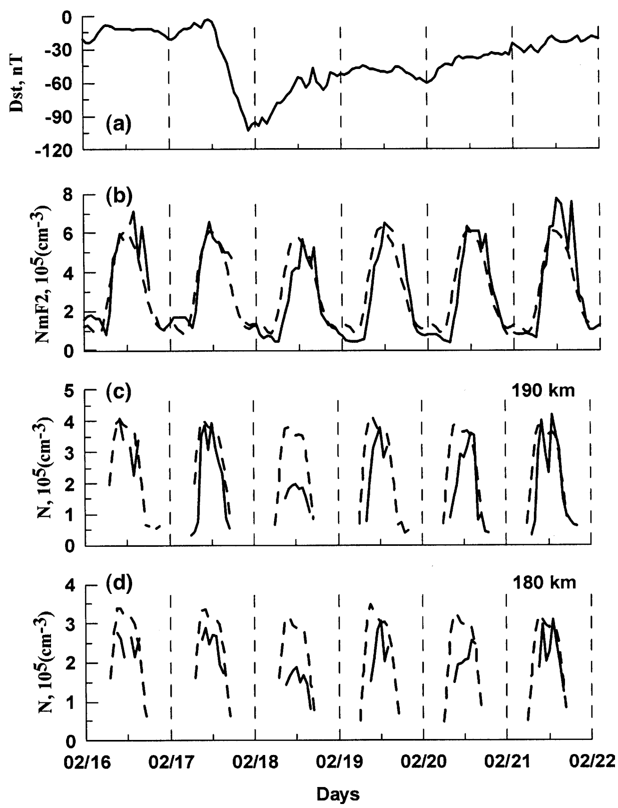

Fig. 5. Storm of February 1998: (a) hourly Dst indices, (b) measured and IRI model predicted NmF2 values for Pruhonice, (c) measured and IRI-predicted electron density courses at 190 km for Pruhonice, (d) the same for 180 km. The observed values are shown as solid lines. The IRI model values are shown as dash lines. Time is in UT.

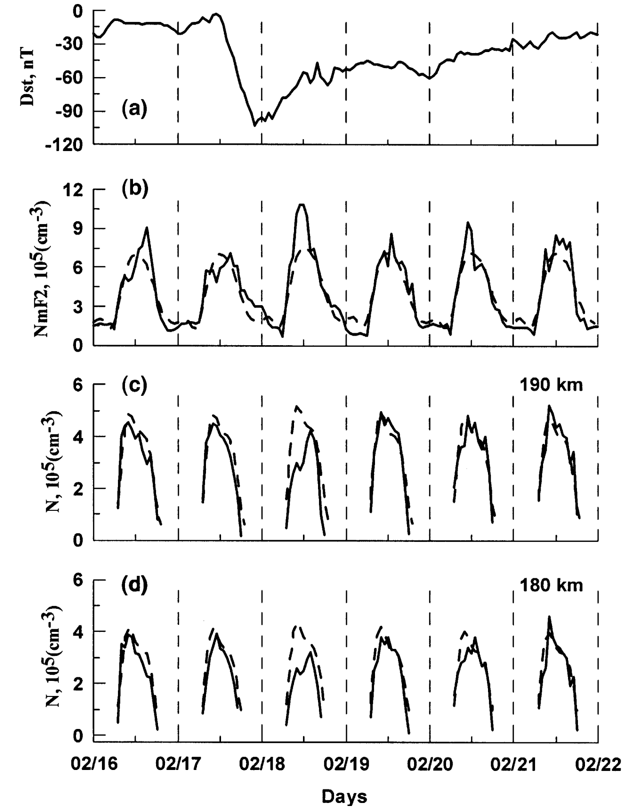

Fig. 6. Storm of February 1998: (a) hourly Dst indices, (b) measured and IRI model predicted NmF2 values for Ebro, (c) measured and IRI-predicted electron density courses at 190 km for Ebro, (d) the same for 180 km. The observed values are shown as solid lines. The IRI model values are shown as dash lines. Time is in UT.

effect in N_mF2 and a decrease in the electron density at 180 and 190 km during the storm main phase. For Pruhonice the IRI model underestimated the F2-layer peak electron density on 13 and 14 November, but in general showed reasonably good agreement with the observations (Fig. 7(a)). In the case of Arenosillo, the model underestimated daytime N_mF2 for the storm main phase and overestimated the nighttime values for the entire period analysed (Fig. 8(a)). Comparison of the measurements with predictions made by IRI reveals that the model overestimates substantially the F1-region electron density at both locations (Figs. 7(c)–(d) and 8(c)–(d)).

As can be seen from Figs. 9 and 10, the F1-region response to the July 2000 super storm seems to be comparable with the response to the above February and November 1998 events, at least at the European middle latitudes. In contrast to the F2 region (Fig. 9(b) and 10(b)), the F1 region did not undergo such large changes. A moderate decrease in electron concentration was recorded for both Pruhonice and Ebro during the storm main phase (Figs. 9(c)–(d) and 10(c)–(d)). The IRI reproduced the N_mF2 variations quite well at both stations while it underestimated the daytime electron density at 190 and 180 km for the entire period analysed.

For brevity, only the results for three geomagnetic storms have been presented. We have analysed 24 events altogether, occurring during different seasons over the period from 1994 to 2003. All these events have been investigated individually. Observed N_mF2 values have been compared with the IRI-predicted ones and the pattern of discrepancies was found to be consistent with the above-presented results.

4. Parameter D_1 for Ebro station

In the previous IRI model, IRI-90, the F1 function has one adjustable parameter, C_1. The model had a prescribed C_1 value for a given location and time. Reinisch and Huang (2000) proposed a new IRI F1-layer profile extending from the F1 peak down to the top height of the valley and introduced a new parameter D_1 determined as a function of latitude, season and solar activity. The D_1 parameter indicates the presence of the F1 layer (for $D_1 = 0$, there is no F1 layer). A reasonable fit to actual profiles was obtained by using $D_1 = 2.5C_1$ (Reinisch and Huang, 2000). A new true height program, version NHPC420, automatically calculates the

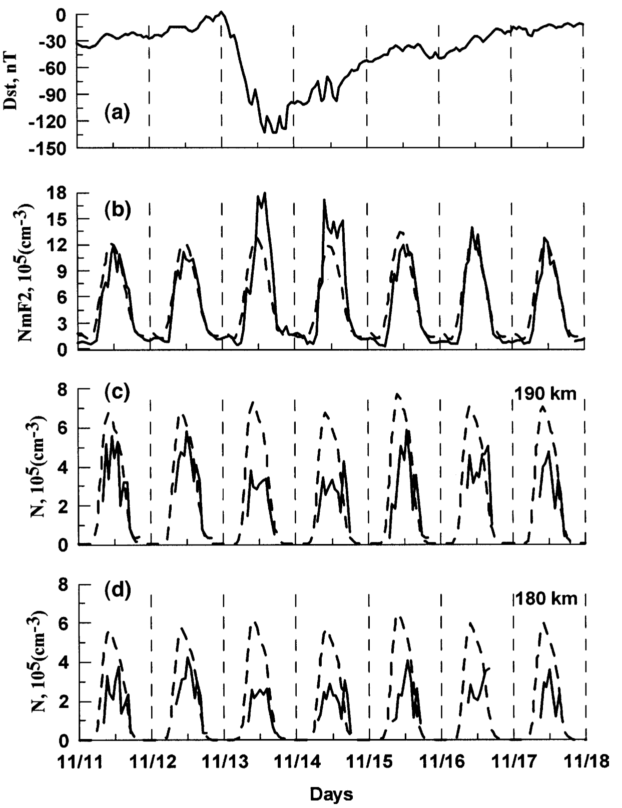

Fig. 7. Storm of November 1998: (a) hourly Dst indices, (b) measured and IRI model predicted N_mF2 values for Pruhonice, (c) measured and IRI-predicted electron density courses at 190 km for Pruhonice, (d) the same for 180 km. The observed values are shown as solid lines. The IRI model values are shown as dash lines. Time is in UT.

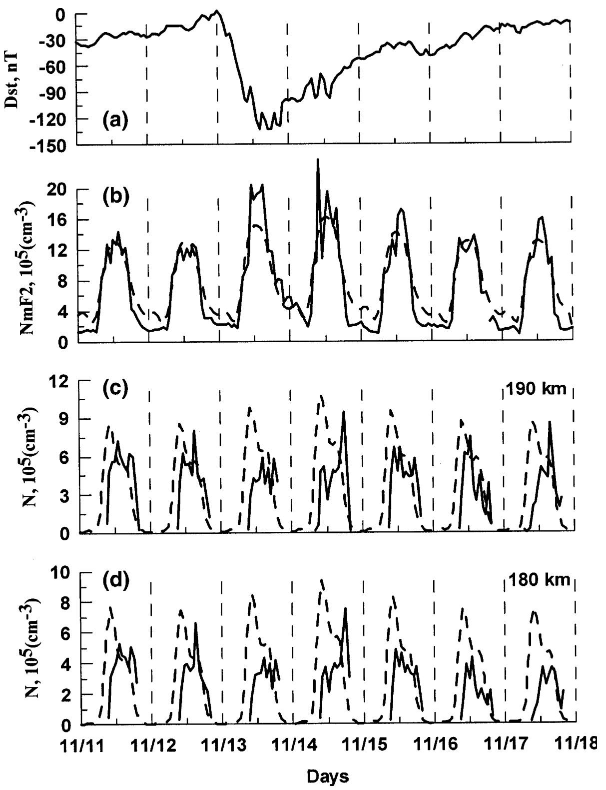

Fig. 8. Storm of November 1998: (a) hourly Dst indices, (b) measured and IRI model predicted N_mF2 values for Arenosillo, (c) measured and IRI-predicted electron density courses at 190 km for Arenosillo, (d) the same for 180 km. The observed values are shown as solid lines. The IRI model values are shown as dash lines. Time is in UT.

D_1, as well as $B0$ (parameter of the thickness of the bottomside of the F2 layer) and $B1$ (parameter of the shape of the electron density profile below the F2 peak) parameters.

We have collected D_1 parameter values for Ebro station for the period from 1998 to 2002. Fig. 11 shows the mass plot of the parameter against time in comparison with the Dst index and sunspot number. As expected, D_1 (i.e. F1 layer) is better developed during lower solar activity and during summer conditions. However, under moderate solar activity (1998) D_1 is quite well developed during winter as well. Fig. 12 depicts the daily occurrence and the magnitude of the D_1 index for years 1998–2002. The figure shows the greatest occurrence of D_1 and highest values during midday. In general, the most frequent value of the parameter D_1 is between 0.5 and 1.0. This pattern reflects the expected pattern of occurrence of the F1 layer. So, D_1 is a good indicator of the F1-layer occurrence.

5. Conclusions

Comparative analyses presented in this paper show that the improved IRI 2000 model with the introduced f_oF2 storm option generally provides a good description of the distribution of the mean N_mF2 for the European middle latitudes. Nevertheless, results show that the model does not always estimate correctly the phase and magnitude of geomagnetic storm effects on the daytime F2-layer peak electron density. During the nighttime discrepancies also exist under quiet geomagnetic conditions and mainly during the winter months. The IRI model underestimates the observed values for January 1996 for both Pruhonice and Ebro stations. The N_mF2 predicted by the IRI model for July 1998 shows significant disagreement with observations during the afternoon hours. The model underestimates F2-layer peak electron density for Pruhonice and overestimates N_mF2 for Ebro.

Compared to the predictions of N_mF2, the daytime F1-region electron density distribution predicted by the IRI model, in general, shows worse agreement with observations. Large deviations from the observed daytime electron density distribution at fixed F1-region heights, and a completely different variation with time below 190 km has been found for Ebro and Pruhonice, for January 1996. The IRI substantially overestimates F1-region electron density during fall-winter geomagnetic storms main phase, as well as for all of the

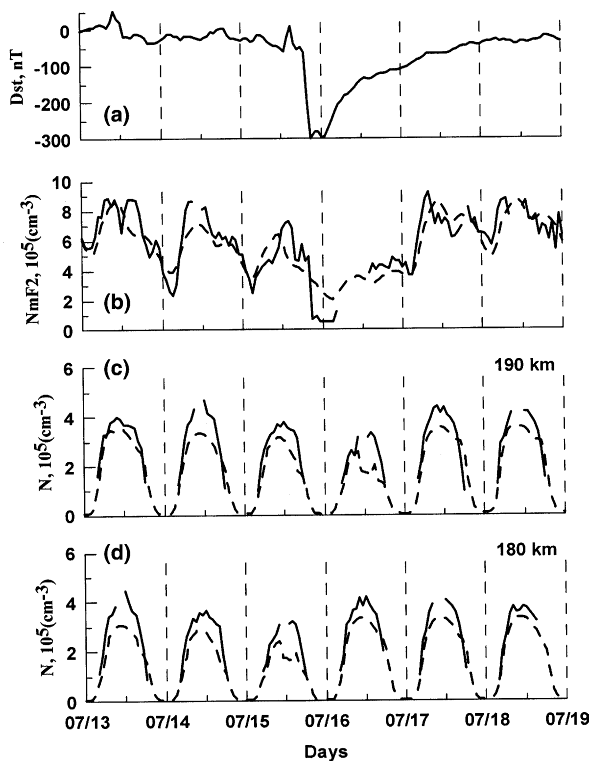

Fig. 9. Superstorm of July 2000: (a) hourly Dst indices, (b) measured and IRI model predicted N_mF2 values for Pruhonice, (c) measured and IRI-predicted electron density courses at 190 km for Pruhonice, (d) the same for 180 km. The observed values are shown as solid lines. The IRI model values are shown as dash lines. Time is in UT.

November 1998 storm period that was analysed. However, for the July 2000 geomagnetic superstorm, effects were overestimated by the IRI.

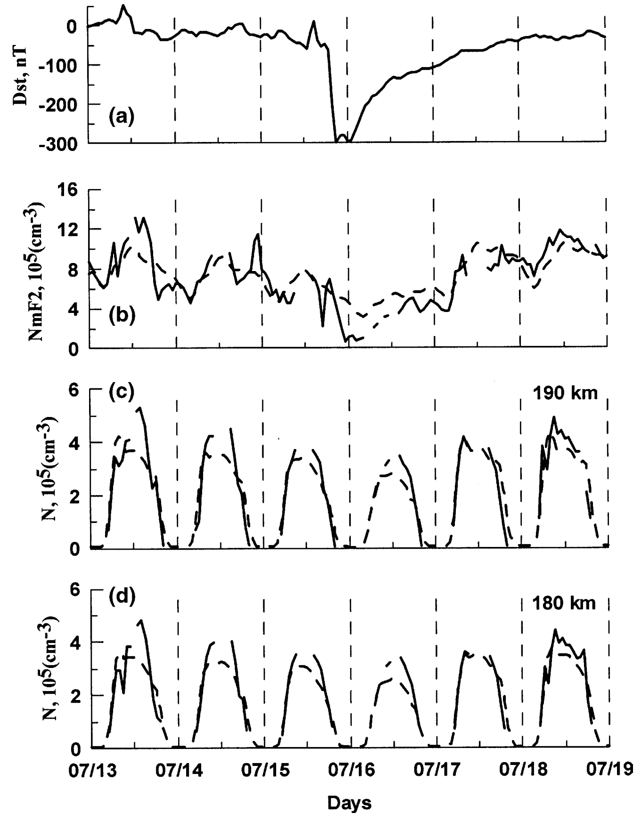

Fig. 10. Superstorm of July 2000: (a) hourly Dst indices, (b) measured and IRI model predicted N_mF2 values for Ebro, (c) measured and IRI-predicted electron density courses at 190 km for Ebro, (d) the same for 180 km. The observed values are shown as solid lines. The IRI model values are shown as dash lines. Time is in UT.

To supply users with more realistic real-time $N(h)$ profiles, the IRI model needs to provide a better representation of the F1-region electron density distribution

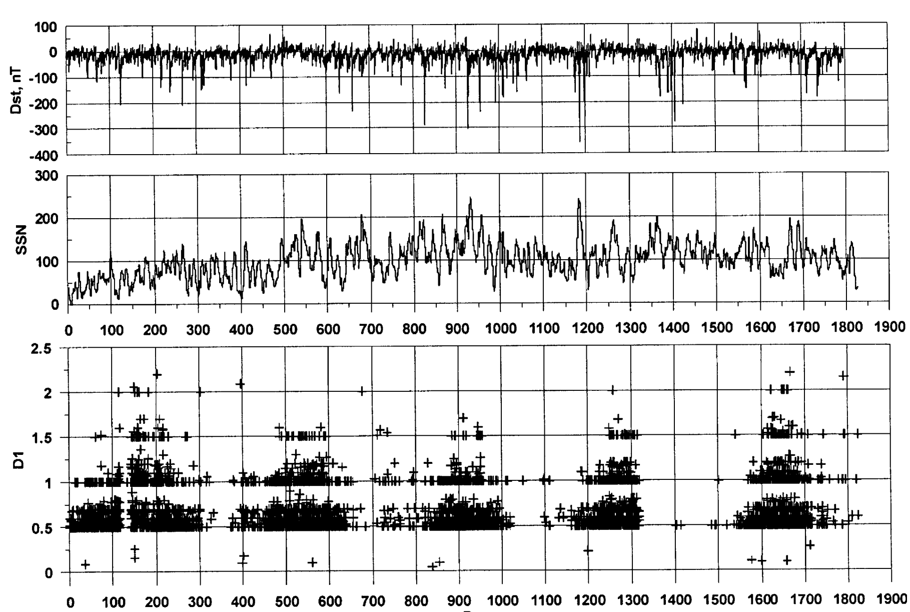

Fig. 11. A scatter plot of the D_1 parameter obtained from Ebro station (bottom panel) against time in comparison with Dst indices (top panel) and sunspot numbers (middle panel) for the period from 1998 to 2002.

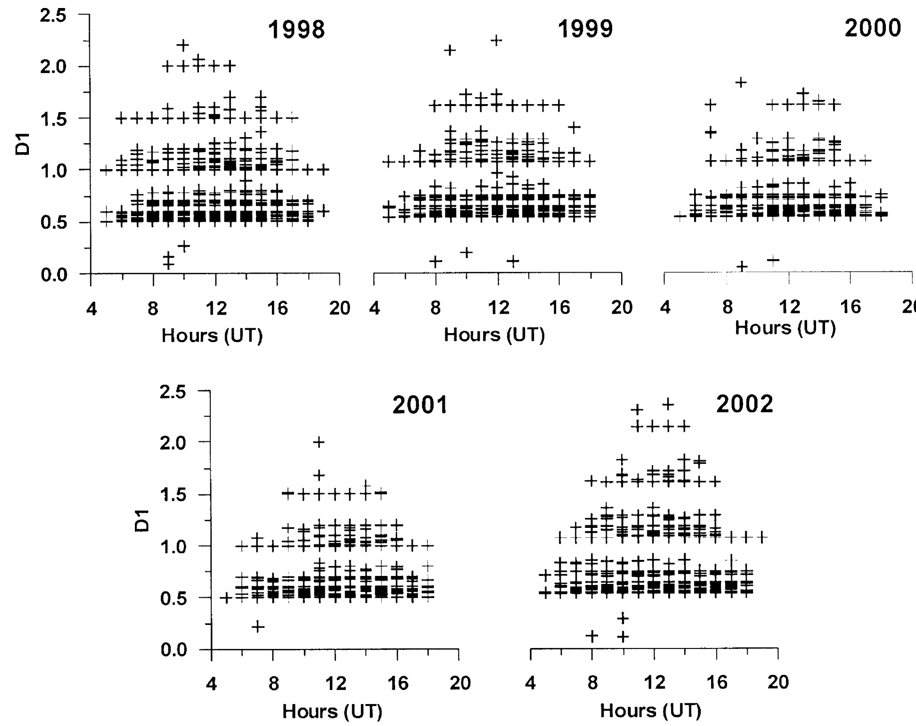

Fig. 12. A scatter plot showing daytime variation of the parameter D_1 for Ebro station for the period from 1998 to 2002.

over Europe for both geomagnetically quiet and disturbed conditions.

The analysis of a set of D_1 values for Ebro station shows that the parameter seems to be a good indicator of the F1 layer for European middle latitudes. The analysis is not conclusive due to the limited data set. We are compiling a larger D_1 database and in particular, the diurnal behaviour of D_1 as a function of season and solar activity will be studied using Arenosillo data.

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