Evaluation of International Reference Ionosphere 2000 at a midlatitude station

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[1] To check the validity of the latest version of the International Reference Ionosphere (IRI-2000), which contains geomagnetic activity dependence based on an empirical storm time ionospheric correction (STORM model), comparison of measured f_oF_2 values with those obtained from the model was made. To quantify the degree of accuracy of the IRI-2000 model during disturbed conditions, the relative difference between the model outputs (with STORM model turned on and turned off options) and experimental data was calculated. The ionosonde f_oF_2 data used were obtained at Ebro Observatory (40.8°N, 0.49°E; geomagnetic latitude 43.2°N) during intense geomagnetic storms occurring in the years 2000 and 2001 (high solar activity). Although only a few case study comparisons have been made, the results show that during storm conditions, predicted values with the STORM model included in IRI-2000 follow the variations of f_oF_2 data better than IRI-2000 without the STORM model. In general, IRI-2000 with the STORM model has almost 30–40% improvement over IRI-2000 without the STORM model. The greater deviations between model outputs and observations are observed during the end of the main phase and early stage of the recovery phase. For this station, in general, IRI predictions with the STORM model underestimate f_oF_2 data in February–March and significantly overestimate them in April–May.

1. Introduction

[2] The knowledge of f_oF_2 both in quiet and perturbed conditions is fundamental for predicting ionospheric characteristics for radio wave propagation, static or dynamic positioning, etc. Significant changes in key ionospheric F_2 region parameters such as the critical frequency f_oF_2 which can last for several days are produced during geomagnetic storms. The ionospheric effects at different ionospheric stations may be quite different during the same geomagnetic storm depending on the station location, local time of the geomagnetic disturbance onset and some other parameters (season, stage of the storm development).

[3] Several physical, empirical and semiempirical models [e.g., *Anderson*, 1973; *Barghausen et al.*, 1969; *Bent et al.*, 1976; *Llewellyn and Bent*, 1973; *Anderson et al.*, 1987; *Bilitza*, 1990] have been developed to predict ionospheric variables during quiet conditions.

[4] One of the most widely used empirical models to predict ionospheric parameters during quiet conditions has been the International Reference Ionosphere (IRI) [*Bilitza*, 1990, 2001]. This model is continuously revised and updated through an international cooperative effort sponsored by the Committee on Space Research and the International Union of Radio Science. The latest version of the International Reference Ionosphere, IRI-2000, has been recently presented [*Bilitza*, 2001] and it contains a geomagnetic activity dependence based on an empirical storm-time ionospheric correction model STORM [*Araujo-Pradere and Fuller-Rowell*, 2000]. This storm time correction model was designed to be dependent on the intensity of the storm and a function of latitude and season [*Araujo-Pradere et al.*, 2004].

[5] In this paper, ground-based digisonde f_oF_2 data from a midlatitude station for several intense geomagnetic storms (peak $Dst < -100$ nT) occurring in the years 2000 ($Rz_{12} = 117$) and 2001 ($Rz_{12} = 111$) are used to check the validity of the IRI-2000 model (with the storm correction) to predict this ionospheric parameter. The

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Table 1. Geomagnetic Storms Used in the Study

Date	Sudden Commencement, UT	Minimum *Dst*, nT
12 Feb 2000	03	−169
6 Apr 2000	10	−321
23 May 2000	19	−147
19 Mar 2001	10	−165
11 Apr 2001	13	−256

ionosonde selected, Ebro Observatory (40.8°N, 0.49°E; geomagnetic latitude 43.2°N) was not used in previous IRI validations [e.g., *Araujo-Pradere and Fuller-Rowell*, 2001; *Araujo-Pradere et al.*, 2004].

[6] The IRI-2000 model (http://modelweb.gsfc.nasa.gov/models/iri.html) has two options to provide the critical frequency: f_oF_2 with the STORM model turned on and f_oF_2 with the STORM model turned off. To quantify the improvement with storm-time model both the model outputs were compared with the observations.

2. Data and Results

[7] The date and onset time of the sudden commencements (SC) of the selected storms are listed in Table 1. The *Dst* geomagnetic index was used to specify the different phases of the storms.

[8] The study has been carried out using hourly values of the critical frequency of F_2 layer from Ebro Observatory (40.8°N, 0.49°E; geomagnetic latitude 43.2°N). As an index to quantify the accuracy of IRI prediction, relative deviations between IRI-2000 outputs (with the STORM model turned on and the STORM model turned off) and f_oF_2 measured values were used. The f_oF_2 data during quiet conditions (not showed here) have geophysical variability but almost coincide with the output of IRI without the STORM model.

[9] The top plot of Figure 1 shows the evolution of *Dst* and *Ap* geomagnetic indexes for the 10–13 February 2000 storm period. The SC (associated with the initial storm phase caused by the interaction of a solar wind disturbance with the geomagnetic field) occurred at about 0300 LT on 12 February. UT and LT are the same because the longitude is close to zero. After the initial phase, *Dst* underwent a steep negative change (main storm phase) caused by the growth of the ring current in the magnetosphere until 1200 LT on storm day. Finally, *Dst* values gradually recovered toward prestorm levels (recovery storm phase) while the ring current is decaying. The middle plot of Figure 1 presents the behavior of f_oF_2 data (solid circles) and superposed both the IRI predictions, the STORM model turned on (thin line) and the STORM model turned off (dashed line). It can be seen that both the IRI outputs (with and without storm model) follow the f_oF_2 variations, with a slight under-

estimation of experimental values during the end of main phase and early stage of the recovery phase. In that period, predictions with the STORM model are closer to f_oF_2 measurements. The relative differences, in percentage, between predicted and experimental values are also represented in the bottom plot of Figure 1. An oscillating behavior and no significant differences between both options during storm period are observed. In general,
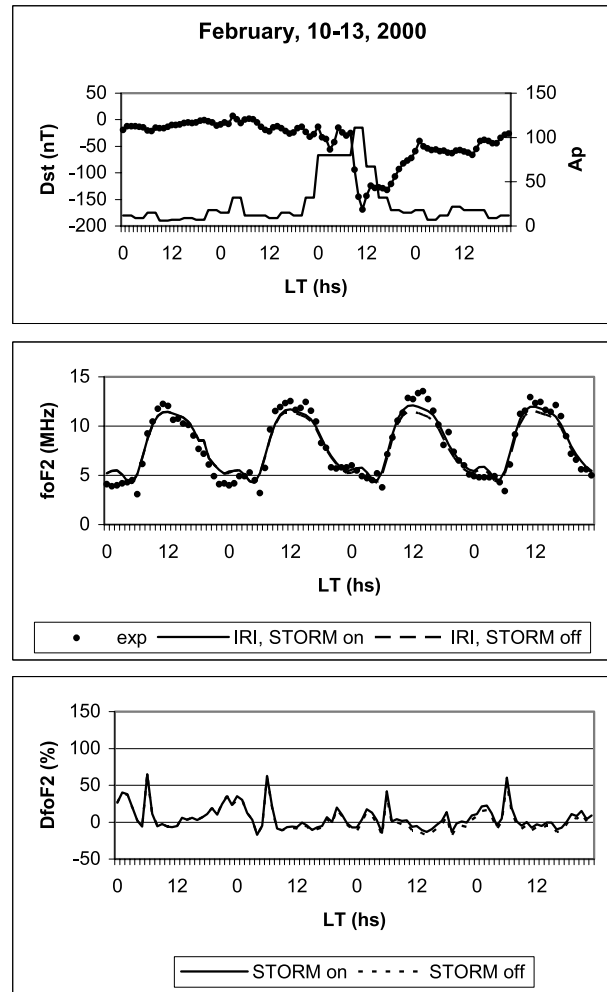

Figure 1. (top) Temporal variation of *Dst* and *Ap* geomagnetic indexes, (middle) f_oF_2 data (solid circles) and outputs of the IRI-2000 model with and without STORM model, and (bottom) relative differences between predicted and measured values for the 10–13 February 2000 storm period. The solid line represents the IRI-2000 output with the STORM model, while the dashed line represents the IRI-2000 output without the STORM model.
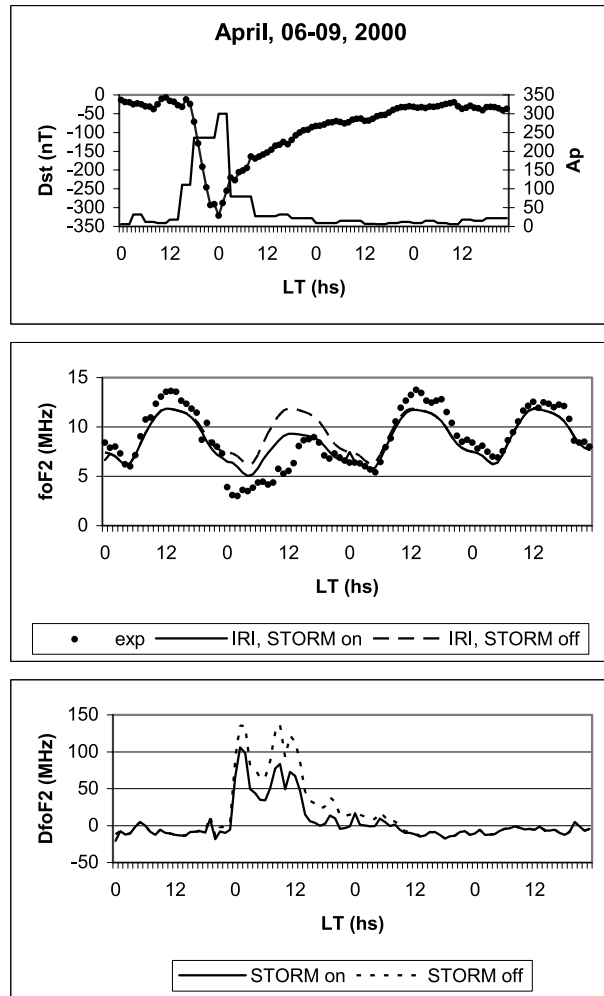
Figure 2. Same as in Figure 1 but for the 6–9 April 2000 storm period.

during the growth and subsequent initial decrease of *Dst* relative deviations are lower than 20%.

[10] Figure 2 presents the variations of *Dst*, *Ap* and f_oF_2 values for the 6–9 April 2000 storm period in the same format as Figure 1. The SC occurred at 1000 LT on 6 April. The main phase lasted until around midnight, followed by a steady recovery. The plot for storm time f_oF_2 variations shows that IRI prediction with the STORM model follows the f_oF_2 behavior while IRI prediction without the STORM model does not capture the changes of measured values and a significant over-estimation occurs during the end of main phase and early part of the recovery phase. In these storm stages IRI output with the storm time model is closer to experimental values. During the development of the main phase the overestimation reaches about 100% and

130% with the STORM model turned on and off, respectively; it is reduced until about 30% and 60% during the end of this stage, increasing again in the beginning of the recovery up to values near 80% and 140%.

[11] The top plot of Figure 3 shows the behavior of *Dst* and *Ap* for the 23–26 May 2000 storm. In this storm the main phase lasted until around 0800 LT on 24 May followed by a long-lasting recovery. An oscil-lating behavior presents f_oF_2 measurements during the storm development. However, predicted values follow the variations of measured values, being the poorest agreement when the STORM model in IRI is turned off. The maximum difference from f_oF_2 storm time values occurs during the early stage of recovery: the overestimation is of about 50% or higher when the STORM model is not operative while is of about 30–40% when the STORM model is included in IRI. After that, the relative differences are in general lower than 30% and 10%, respectively.
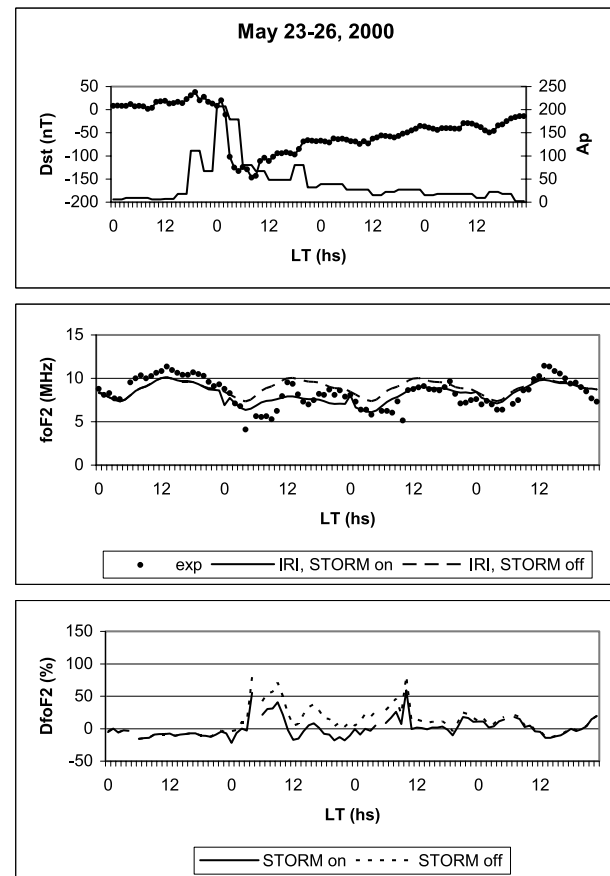

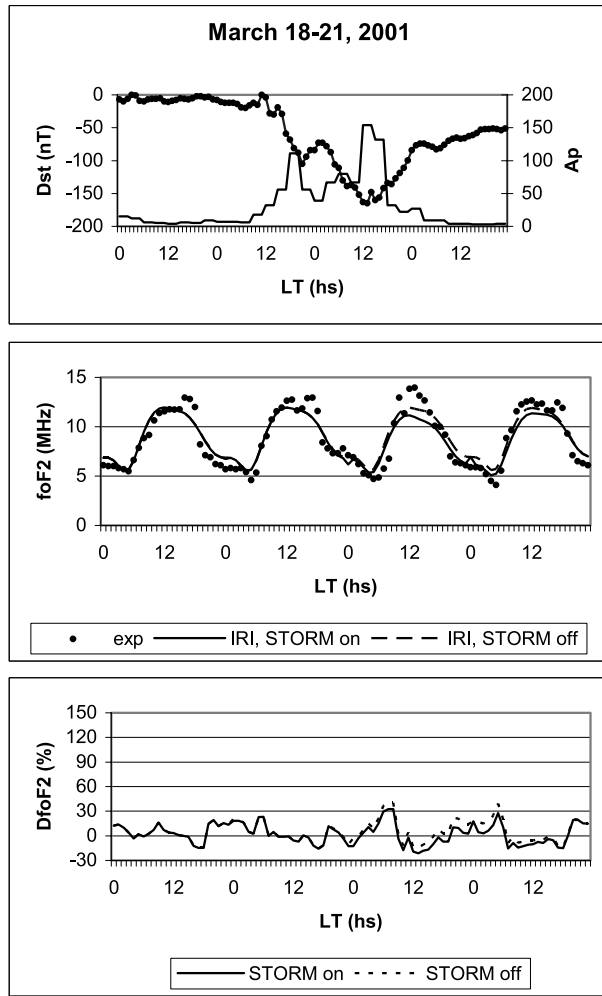**Figure 3.** Same as in Figure 1 but for the 23–26 May 2000 storm period.

March 18-21, 2001

Figure 4. Same as in Figure 1 but for the 18−21 March 2001 storm period.

[12] Figure 4 presents the variations of *Dst*, *Ap* and f_oF_2 for the 18−21 March 2001 storm period. An irregular and long-lasting main phase remained until around local noon on 20 March, followed by a relatively rapid recovery. It can be seen an underestimation of experimental f_oF_2 values during the end of main phase and the first part of the recovery phase. Moreover, there is no significant difference between both IRI predictions. During the growth of the storm the amplitude of relative difference does no exceed 40%. During the initial stage of recovery, relative deviations are negative (less than 10 – 20%). After that they change its sign, being the best adjustment with the STORM model in IRI-2000.

[13] Figure 5 presents the variations of *Dst*, *Ap*, f_oF_2 data and the predictions of the IRI model for 11−14 April 2001. The main phase lasted until around midnight on storm onset day and it was followed by a long-duration

recovery. The IRI output with storm time model shows a better agreement with the observations. However, both the IRI outputs overestimate the measured values during the end of main phase and the initial part of recovery and they underestimate during the end of the recovery. The maximum disagreement among predicted and measured frequencies occurs during the early stage of the recovery, when the amplitude of the relative difference reaches 90% and 130% (with the STORM model turned on and turned off, respectively). After that, the underestimation is lower than 10%.

3. Discussion and Conclusions

[14] The response of the empirical storm-time correction model STORM in IRI-2000 has been checked at a
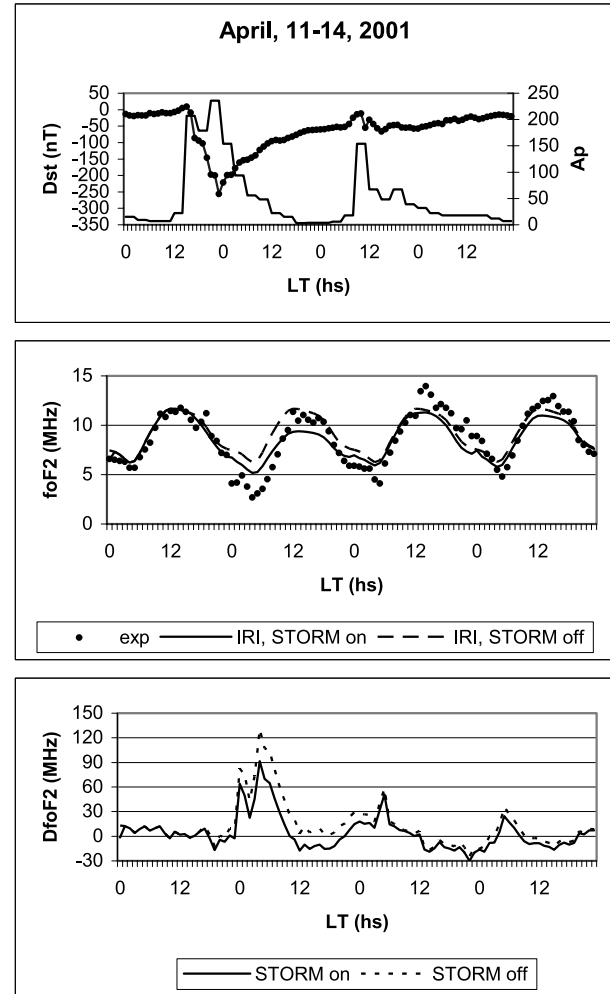
April, 11-14, 2001

Figure 5. Same as in Figure 1 but for the 11−14 April 2001 storm period.

station not used previously in IRI validations. To this end, the IRI model outputs (with and without the STORM model) were compared with f_oF_2 observations measured at Ebro Observatory during geomagnetic storms occurred in two years of high solar activity: 2000 ($Rz_{12} = 117$) and 2001 ($Rz_{12} = 111$).

[15] In general IRI prediction with the STORM model follows the changes in f_oF_2 but it does not reproduce well the experimental values during the main phase and first part of the recovery phase of the storms. Similar results were found during storms occurred in 1993, 1995 and 1999 by considering data from another midlatitude ionosonde station not included in the model development [*Mansilla et al.*, 2004].

[16] The results here show that IRI-2000 with storm time model has almost 30–40% improvement over IRI-2000 without the STORM model because the relative differences between predicted and measured f_oF_2 values are reduced in that order of magnitude.

[17] During the end of the main phase and first part of the recovery of the storms for this station the results indicate an underestimation of measured f_oF_2 values in February–March and a significant overestimation in April–May. Previous to the storm onset and during the end of the recovery phase similar values are observed with both IRI predictions and in general there is no significant difference between IRI and observations.

[18] Although a few checks have been made the magnitude of the improvement seems to indicate a seasonal dependence, being the best agreement in winter and near vernal equinox and the poorest agreement between equinox and solstice (April–May). However, *Araujo-Pradere et al.* [2003] found that the quality of the IRI-2000 prediction is the best in summer and also in equinox conditions.

[19] A characteristic of the ionospheric F_2 region during geomagnetic storms is the great degree of variability. At middle latitudes peak electron density of F_2 region N_mF_2 (proportional to the square of the critical frequency) may be enhanced (positive ionospheric storm) and/or depressed (negative ionospheric storm) during storm periods. However, data analysis from ground-based ionosondes has demonstrated that decreases in N_mF_2 during the main phase of a storm at midlatitudes seem to be the typical response of the F_2 region, especially in summer and between the equinox and the solstice [e.g., *Rishbeth*, 1998; *Szuszczewicz et al*, 1998; *Blagoveshchensky et al.*, 2003].

[20] It is well known that negative ionospheric storm effects are caused by changes in the thermospheric composition mainly increases in the molecular nitrogen to atomic oxygen (N_2/O) ratio. Such composition changes alter the balance between electron production and loss rates resulting in N_mF_2 decreases. The storm-induced circulation driven by high-latitude energy inputs (Joule heating and particle precipitation) is directed equatorward. In summer, the background (quiet) circulation is all the day through directed equatorward and coincides with the storm-induced circulation which is favorable for penetration of air with increased N_2/O to middle latitudes, and so negative ionospheric storms are observed both in the daytime and at night (see *Danilov* [2001] for details). Since several hours are required for the generation and propagation from high to middle latitudes of these storm winds any effect produced by them is expected to be produced with a time delay of 4–5 hours after SC.

[21] As was already mentioned, IRI model captures the direction of the f_oF_2 changes but it significant overestimates the observations in May 2000–2001 and April 2001. The negative storm effects produced during the end of the main phase and first stage of the recovery phase (see f_oF_2 data and the model output without the STORM model for comparison) are not well reproduced by the model. Although the STORM model considers that the seasonal circulation transports composition changes to midlatitudes particularly during the summer seasons, possibly a stronger dependence with the storm time circulation could be considered during intense geomagnetic storms.

[22] There is an increase in the variability of the ionospheric response to geomagnetic storms in winter. In the daytime the background circulation (poleward) stops the storm-induced circulation and so the region of the negative effects is confined at high latitudes. However, it is not always the case because the storm circulation is sometimes so strong that even at daytime that the background circulation is not able to stop it. During the nighttime the two circulation (the background and storm-induced ones) coincide (they both are equatorward) and so the air with disturbed N_2/O ratio spreads out to much lower latitudes than in the daytime. Therefore one can expect more difficulty to predict the ionospheric response to a geomagnetic storm. However, for this station the results show that on the storm on 10–13 February 2000 the STORM model prediction presents better adjustment with observations than during equinox conditions. This is possibly due to a delayed small positive ionospheric storm effect observed during the first stage of the recovery for which predicted values are no significant different to the data since no prominent decreases of electron density as during summer months are produced.

[23] In brief, the results presented here confirm the improvement in IRI-2000 with the STORM model over IRI-2000 with no geomagnetic dependence. However, they emphasize the need to make more validation studies using more stations and also different geomagnetic storm periods in order to try to refine the representation of the observations at different latitudes and seasons.

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