Variability of ionospheric parameters during geomagnetic storms at a middle latitude station: comparisons with IRI model

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Abstract

This paper discusses the behavior of ionospheric parameters that were obtained from electron density profiles derived from ionograms recorded at El Arenosillo (37.1°N, 353.2°E; Dip = 52; Modip = 45.5) during some intense geomagnetic storms. The selected parameters are the critical frequency of the F2 layer, f_oF2, the height of the peak electron density, h_mF2, the thickness and shape parameters of the F2 layer, B0 and B1, and the integrated total electron content (ITEC). As a measure of the ionospheric disturbance during the storms the relative deviations of these parameters from their corresponding monthly medians has been calculated. All the parameters present changes during the storms. In general, increases during the main phase and first stage of the recovery phase are observed. The relative deviations of f_oF2 and ITEC present similar temporal behavior (as during quiet geomagnetic conditions). Comparisons between f_oF2 and ITEC with IRI 2001 model predictions show that the model significantly overestimates the ionospheric parameters mainly during the recovery phase of the storms.

Keywords: Geomagnetic storms; Ionospheric variability; International Reference Ionosphere

1. Introduction

Disturbances of the ionosphere in association with geomagnetic storms (called ionospheric storms) have been studied for many decades. All ionospheric characteristics are affected during geomagnetic storms, however the changes in the peak electron density of the F2 layer, N_mF2, have been studied most frequently because it is the most easily accessible characteristic of the ionosphere.

Electric fields, thermospheric meridional winds, a "composition bulge", and high latitude particle precipitation have been suggested as physical mechanisms to explain the ionospheric reaction to geomagnetic storms at different latitudes (e.g., Fuller-Rowell et al., 1994; Prölss, 1995; Buonsanto, 1999; Danilov, 2001). Statistical patterns of ionospheric behavior were described in earlier works. Long-lasting decreases of N_mF2 (the so-called negative ionospheric storms or negative ionospheric effects) are usually preceded by increases of N_mF2 (the so-called positive ionospheric storms or positive ionospheric effects), which can appear during the main phase and in winter at low and mid-latitudes, respectively. This classical picture of ionospheric

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behavior is based on a statistical study reported in reviewers by Matsushita (1959) and Danilov (1985), and is supported by many observations (e.g., Wrenn et al., 1987; Rodger et al., 1989; Rishbeth, 1998; Szuszczewicz et al., 1998). However, the reaction of the ionosphere at different ionospheric stations may be quite different during the same geomagnetic storm.

In this paper an attempt is made to illustrate the variability of some ionospheric characteristics obtained at El Arenosillo (37.1°N, 353.2°E) in response to four intense geomagnetic storms in 1993, 1995 and 1999. The analysis mainly deals with the variations during the main phase and first stage of the recovery of the storms.

We also made a preliminary validation attempt of the IRI 2001 model during magnetic storms (Bilitza, 1986, 1990, 2001;Rawer and Bilitza, 1989, 1990) by comparing the measured N_mF2 and ITEC (defined below) with the IRI model predictions.

2. Data

The data used were hourly values of the critical frequency of the F2 layer, f_oF2 (proportional to the square root of the peak electron density N_mF2), the height of the peak electron density h_mF2, the bottom side thickness parameter B0 and the shape parameter B1 of the F2 layer, and the integrated ionospheric total electron content (ITEC), obtained by using the technique described by Huang and Reinisch (2001). The bottom side electron density profile up to the F2 peak is calculated by inversion of the ionogram (Huang and Reinisch, 1996) and the topside profile is approximated by an alpha-Chapman layer with a constant height scale H derived from the shape of the bottomside profile. The ITEC is calculated by integration over the entire profile.

Table 1 lists the selected geomagnetic storms. All four events presented a sudden commencement (sc). Three storms had the sc during daytime hours (around local noon or local sunset) and one storm during nighttime hours (around local midnight). The D_{st} geomagnetic index (provided by solar–geophysical data prompt reports) was used to define the different phases of the geomagnetic storms.

Table 1
Magnetic storms used in the study

Date	Sudden commencement (UT)	Minimum D_{st} (nT)
April 4, 1993	1434	−161
October 18, 1995	1121	−122
January 13, 1999	1054	−113
October 21, 1999	0224	−231

3. Results

The ionospheric reaction to geomagnetic storms was analyzed on the storm day and the two following days. The degree of perturbation during the storms is characterized by the hourly relative deviation from the monthly median. Fig. 1(a) shows the behavior of D_{st} index during the April 4–6, 1993 storm period. The main phase of the storm lasted until around 07 LT on April 5 followed by a rapid recovery. Fig. 1(b) shows the variability of the relative deviation of f_oF2 for that period. The main phase shows a f_oF2 enhancement of about 100% at 20 LT on April 4; the recovery phase has an oscillating behavior with small positive and negative deviations (about 20–30% change). Enhanced values during the main phase and the early stage of the recovery are also observed for the relative deviation of ITEC (Fig. 1(c)), with similar variability as the f_oF2 deviation. It can be seen that the relative deviations of ITEC are nearly twice that f_oF2. The behavior of the relative deviation of h_mF2 (Fig. 1(d)) indicates an uplifting of the layer peak from around sc until the onset of the recovery phase. Afterward a trend to recover towards the reference values is observed. Figs. 1(e) and (f) show the relative deviations of B0 and B1 respectively. It can be observed that, in general, B0 is up by about 50%, while Bl presents a fluctuating pattern during the storm.

The variations of D_{st} for the October 18–20, 1995 storm period is presented in Fig. 2(a). The storm was characterized by a short duration main phase (until around 23 LT on October 18), followed by a fast recovery. Fig. 2(b) shows the relative deviation of f_oF2 in response to the storm. During the main phase slightly increased values (~20% change) are observed. During the first stage of the recovery there is a large enhancement (exceeding 50%) followed by reduced values during the night time hours. Similar features are observed in the relative deviation of ITEC during the main phase and first stage of the recovery (Fig. 2(c)). As before, the relative deviations of ITEC are greater than corresponding relative deviations of f_oF2. Fig. 2(d) shows the relative deviation for h_mF2, increased values during the end of the main phase and average values during the first stage of the recovery are observed. The greater deviations of h_mF2 are correlated with the greater deviations in f_oF2 and ITEC. Relative deviations of B0 and B1 are shown in Fig. 2(e) and (f). Both of these parameters present very irregular variations. In general, B0 is above the reference values throughout the storm period, while Bl fluctuates randomly.

Fig. 3(a) shows the behavior of D_{st} for January 13–15, 1999. An irregular main phase lasted until around 21 LT on the storm day, followed by a long-duration recovery. The relative deviation of f_oF2 is shown in Fig. 3(b). No significant disturbance effects during the main phase are observed. A considerable enhancement

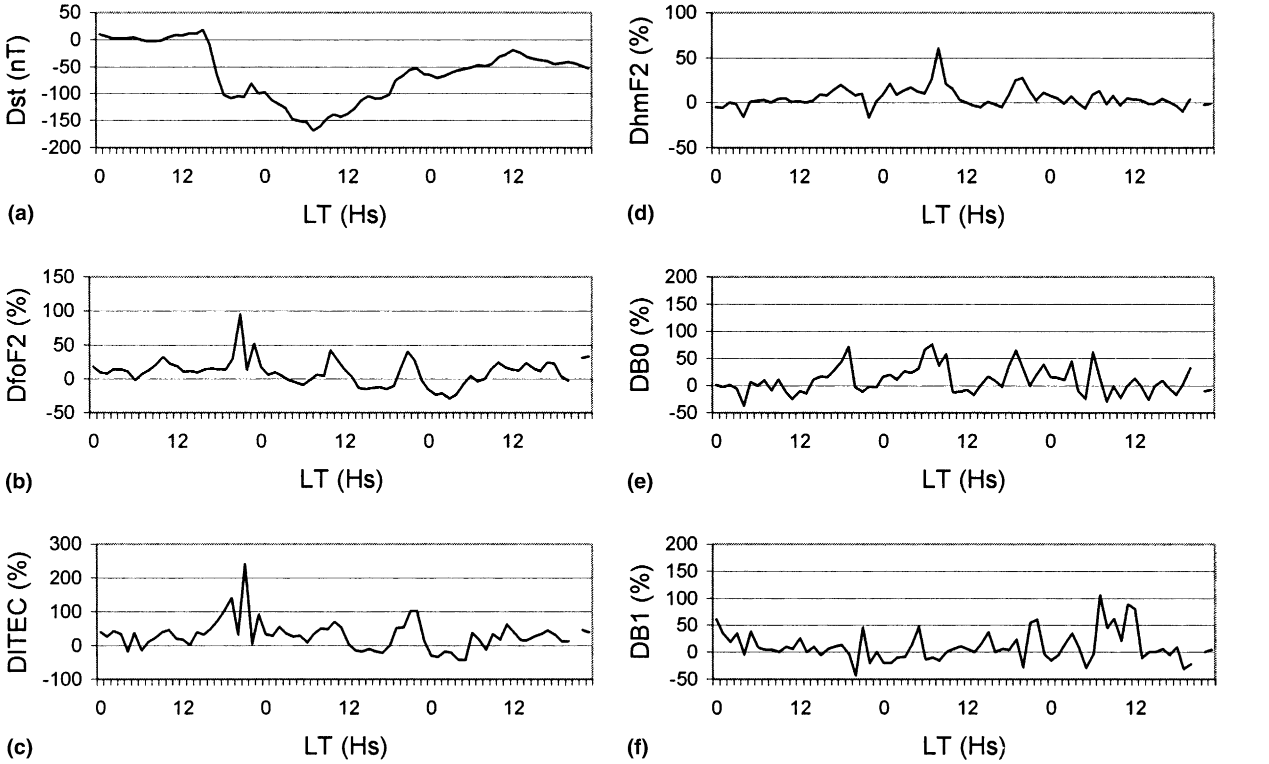

Fig. 1. (a) Behavior of D_{st} for the storm period April 4–6, 1993. Hourly relative deviations from their monthly medians for this period of: (b) f_oF2; (c) ITEC; (d) h_mF2; (e) B0; (f) B1.

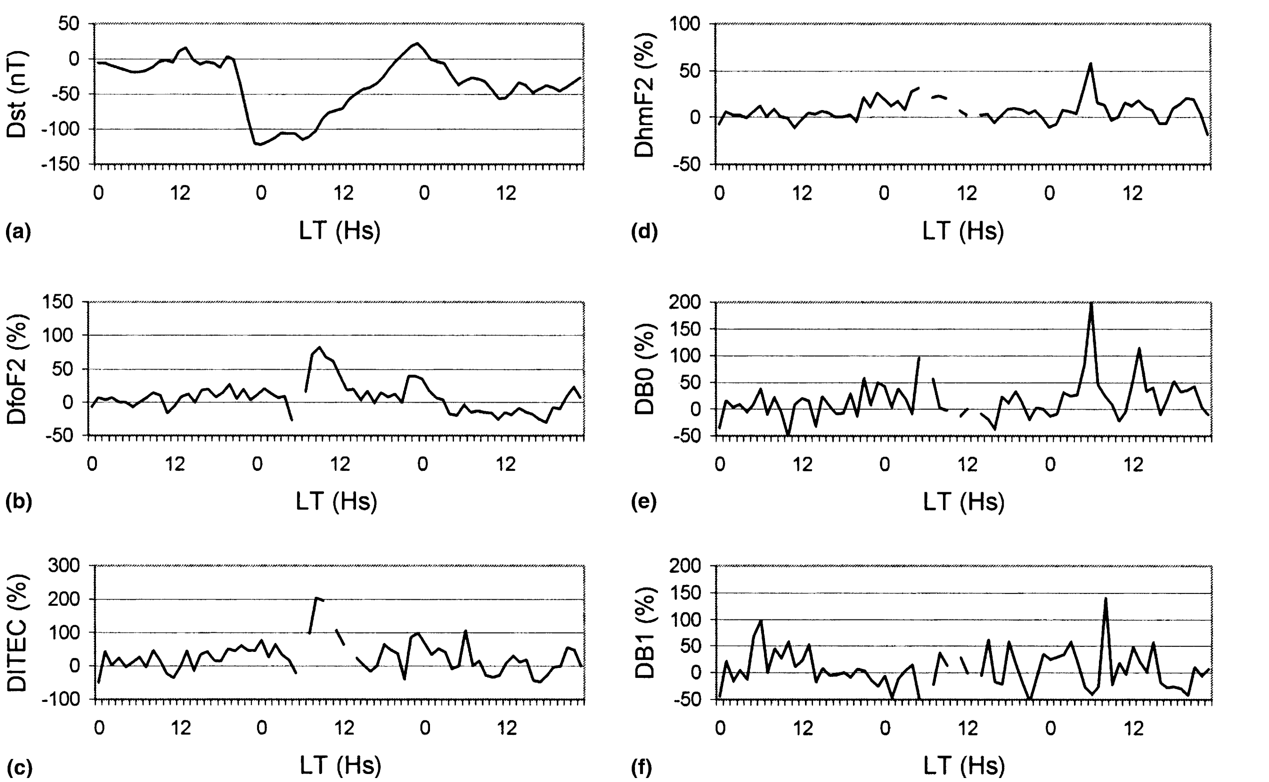

Fig. 2. Same as Fig. 1, but for the October 18–20, 1995 storm period.

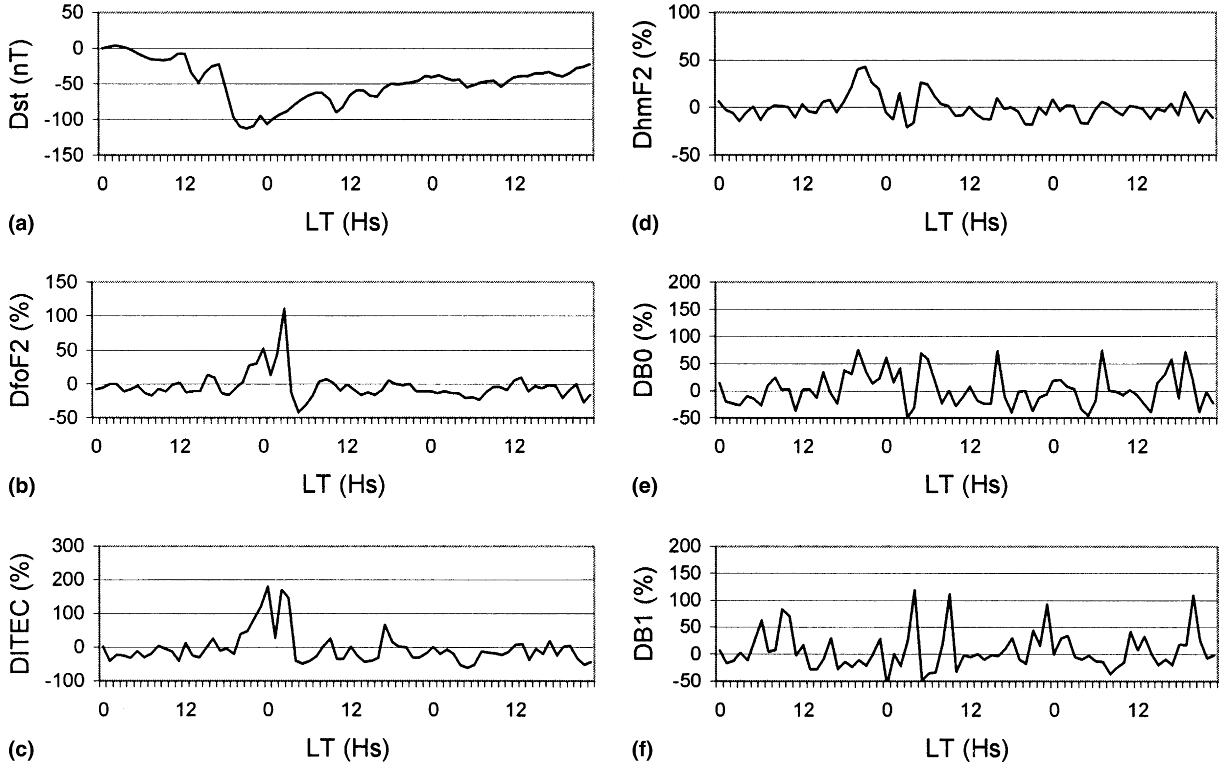

Fig. 3. Same as Fig. 1, but for the January 13–15, 1999 storm period.

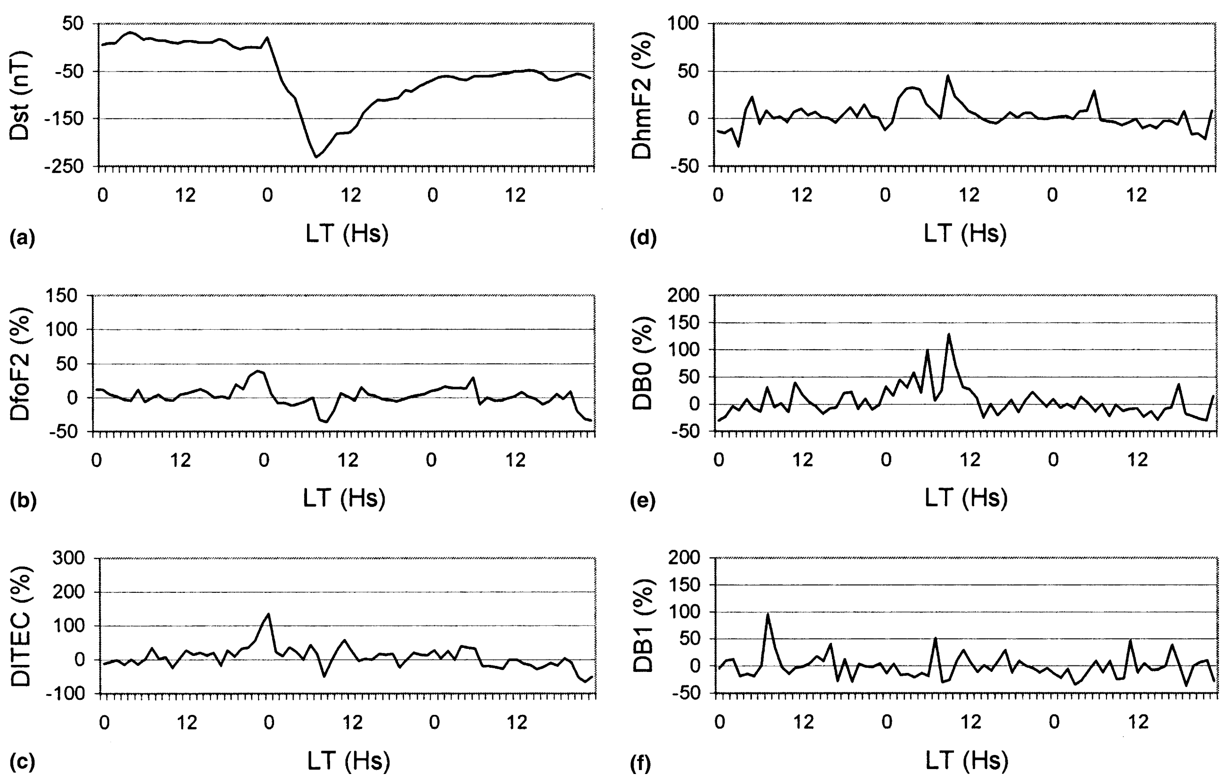

Fig. 4. Same as Fig. 1, but for the October 20–24, 1999 storm period.

lasts for about 7 h with values near 100% at the onset of the recovery (in the night time hours), followed by a short duration depression (5 h) in the morning hours, and a subsequent trend toward the monthly median values. Fig. 3(c) presents the relative deviations of ITEC, which are similar to those observed in f_oF2, for the same period. The higher deviations during the considerable increase are close to 200%. Relative deviation of h_mF2 for the storm is shown in Fig. 3(d). A well-defined increase (~50% change) occurs nearly simultaneous with the f_oF2 and ITEC enhancements. The increase is followed by a decrease and a subsequent trend leveling off to the reference values. In general, irregular behaviors are observed in the relative deviations of B0 and Bl (Figs. 3(e) and (f)). B0 increases only during the main phase, then it is fluctuating, while Bl exhibits an oscillating pattern throughout the storm period.

Fig. 4(a) shows the D_{st} variations for October 21–23, 1999. In this storm, the main phase lasted until 06 LT on October 21 followed by a long duration recovery phase. No significant disturbance in the relative deviation of f_oF2 after sc is observed (Fig. 4(b)). A short duration depression (less than 50%) occurred in the morning hours on October 22 during the first stage of the recovery. The relative deviation of ITEC (Fig. 4(c)) shows a similar behavior as f_oF2, i.e., a small negative deviation followed by a steady recovery to the reference value. Fig. 4(d) shows the relative deviation of h_mF2. Enhanced values that do not exceed 50% are observed from sc up to the recovery phase onset (10–12 LT), when the deviation starts to level off. Figs. 4(e) and (f) show the relative deviations of B0 and Bl, respectively. B0 presents an increase from the sc up to 12 LT on October 21 followed by values close to monthly medians, while Bl presents small and irregular variations throughout the storm period.

The Internet online new version of IRI (IRI 2001) was used to check the validity of this model to predict N_mF2 and TEC under disturbed conditions. In the new version of IRI the user can choose between two f_oF2 models: storm off (quiet conditions) and storm on (disturbed conditions) which give N_mF2 and TEC under

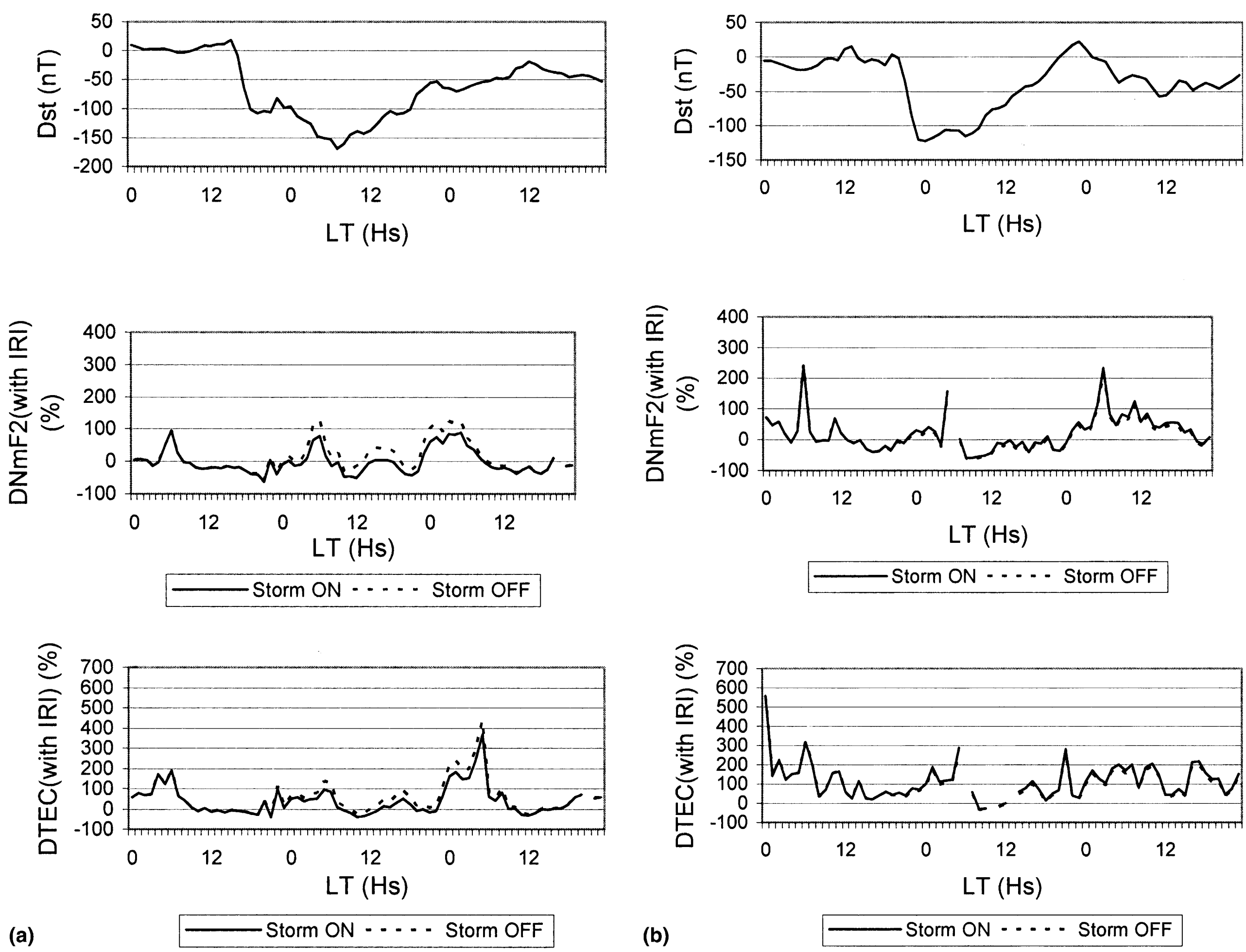

Fig. 5. (a) D_{st} index and relative deviations in percent between IRI predictions and N_mF2 and ITEC data using the IRI2001 "storm on" option and "storm off option for the April 4–6, 1993 storm period. (b) Same as (a), but for the October 18–20, 1995 storm period. Same as (a), but for the January 13–15, 1999 storm period. Same as (a), but for the October 20–24, 1999 storm period.

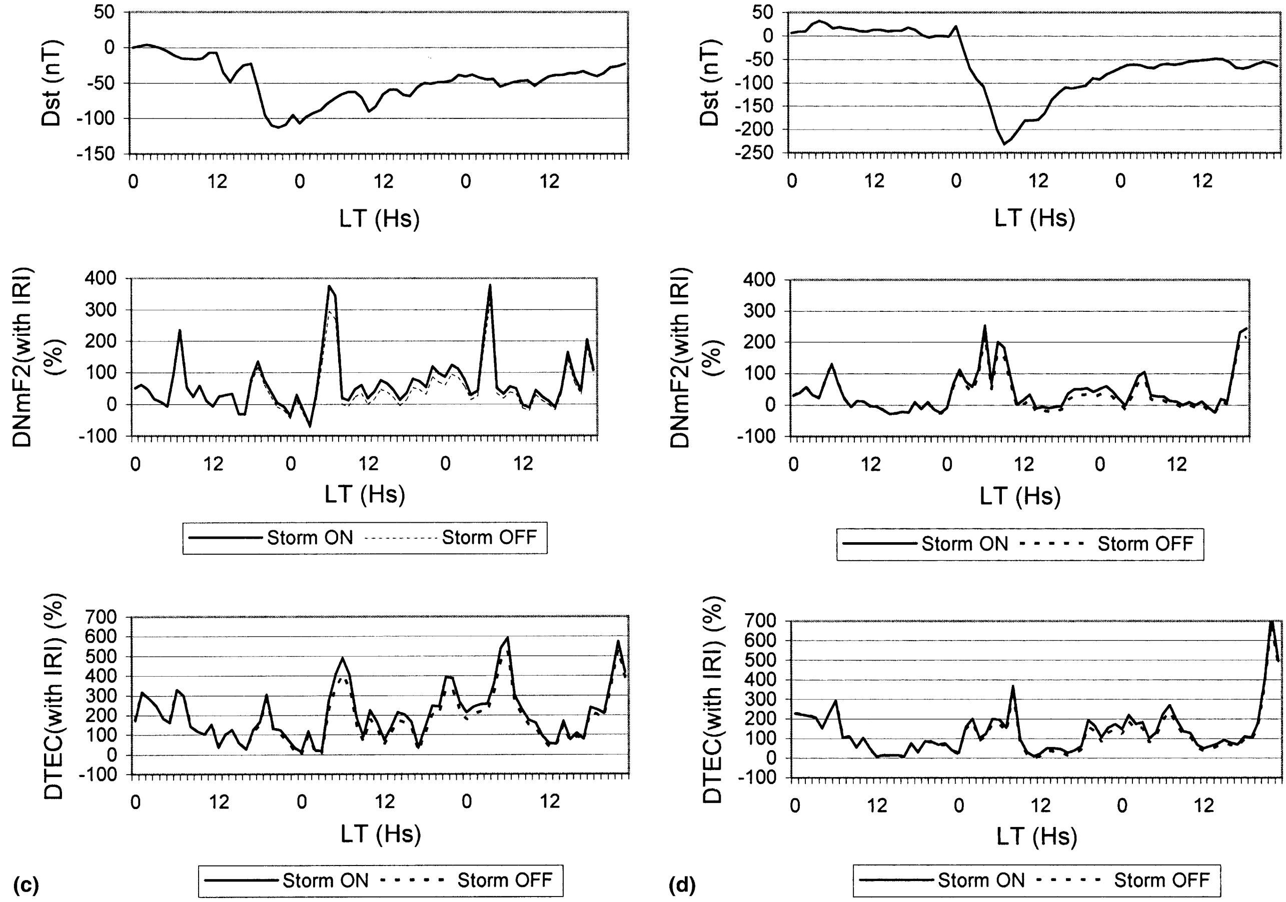

Fig. 5 (*continued*)

quiet and disturbed conditions, respectively. The percentage deviations between IRI predictions and N_mF2 and ITEC data were calculated. Both the options included in the IRI model (storm on and off) were used. Figs. 5(a)–(d) show these relative deviations (DN_mF2 (with IRI) and DTEC (with IRI)) with the two input conditions (storm off and storm on) during the geomagnetic storms of 4 April, 1993, 18 October, 1995, 13 January, 1999, and 21 October, 1999. The development of the D_{st} index during the storms is presented at the top of the figures. There are significant difference between IRI and the data, also when using "storm on" option. In general, IRI overestimates N_mF2 and ITEC data throughout the storm period, the greater deviations occurring during the recovery phase. It can be also noted that relative deviations of ITEC are higher than those of N_mF2.

No significant improvement is achieved by using the "storm on" option in IRI2001. During the storm on 4 April 1993, the "storm on" model predictions are slightly closer to data than those obtained with the "storm off" option. For the other storms, the "storm on" option gives no better, or even worse results than the "storm off" option.

4. Conclusions

The relative deviations of f_oF2 and ITEC during storms behave similarly (this is not different from quiet conditions), suggesting that the knowledge of the variability of one can predict the approximate variability of the other, even during disturbed conditions. We found that for storms that start during daytime hours larger disturbances in f_oF2 and ITEC are produced during the main phase and the first stage of recovery. In general, B0 is enhanced during the main phase and the beginning of the recovery, while B1 presents an oscillating pattern throughout the storm period. It will be necessary also to analyze more cases in which the storm onset occurs during nighttime because during the intense geomagnetic storm on October 21, 1999 no significant storm effects in f_oF2 and ITEC were observed.

The analysis of four selected storms shows that IRI 2001 (even using the "storm on" option) generally overestimates f_oF2 and ITEC, especially during the recovery phase of the storms. This conclusion cannot be generalized, however, since it is based on such a small database.

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References

Bilitza, D. International Reference Ionosphere: recent developments. Radio Sci. 21, 343–346, 1986.

Bilitza, D. International Reference Ionosphere. Report NSSDC/WDC-R & S 90-22. Natl. Space Sci. Data Cent./World Data for Rockets and Satellites, Greenbelt, MD, 1990.

Bilitza, D. International Reference Ionosphere 2000. Radio Sci. 36, 261–276, 2001.

Buonsanto, M.J. Ionospheric storms – a review. Space Sci. Rev. 88, 563–601, 1999.

Danilov, A.D. Ionospheric storms in F2 region. Geomagn. Aeronomy 23, 705–719, 1985.

Danilov, A.D. F2-region response to geomagnetic disturbances. J. Atmos. Terr. Phys. 63, 441–449, 2001.

Fuller-Rowell, T.J., Codrescu, M.V., Moffett, R.J., Quegan, S. Response of the thermosphere and ionosphere to geomagnetic storms. J. Geophys. Res. 99, 3893–3914, 1994.

Huang, X., Reinisch, B.W. Vertical electron density profiles from the digisonde network. Adv. Space Res. 18 (6), 121–129, 1996.

Huang, X., Reinisch, B.W. Vertical electron content from ionograms in real time. Radio Sci. 36, 335–342, 2001.

Matsushita, S. A study of the morphology of ionospheric storms. J. Geophys. Res. 64, 305–321, 1959.

Prölss, G.W. Ionospheric F-region storms. In: Volland, (Ed.), Handbook of Atmospheric Electrodynamics, pp. 195–248, 1995.

Rawer, K., Bilitza, D. Electron density profile description in the IRI. J. Atmos. Terr. Phys. 51, 781–790, 1989.

Rawer, K., Bilitza, D. International Reference Ionosphere-plasma densities: status 1988. Adv. Space Res. 10, 5–14, 1990.

Rishbeth, H. How the thermospheric circulation affects the ionospheric F2-layer. J. Atmos. Terr. Phys. 60, 1385–1402, 1998.

Rodger, A.S., Wrenn, G.L., Rishbeth, H. Geomagnetic storms in the Antarctic F2 region. 2. Physical interpretation. J. Atmos. Terr. Phys. 51, 851–866, 1989.

Szuszczewicz, E.P., Lester, M., Wilkinson, P., Blanchard, P., Abdu, M., Hanbaba, M., Igarashi, K., Pulinets, S., Reddy, B.M. A comparative study of global ionospheric responses to intense magnetic storm conditions. J. Geophys. Res. 103, 11665–11684, 1998.

Wrenn, G.L., Rodger, A.S., Rishbeth, H. Geomagnetic storms in the Antarctic F-region. 1. Diurnal and seasonal patterns for main phase effects. J. Atmos. Terr. Phys. 49, 901–913, 1987.