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Quality of STORM model predictions for a mid-latitude station

E. A. Araujo-Pradere
CIRES, University of Colorado and Space Environment Center NOAA, Boulder, CO., USA

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RESUMEN

Las simulaciones teóricas más recientes de la respuesta ionosférica a tormentas geomagnéticas han sido la base para una mejor comprensión de los procesos involucrados y el consiguiente desarrollo de un modelo empírico ionosférico para condiciones perturbadas (STORM). Este modelo empírico tiene como entrada la historia previa del índice magnético a_p, y está designado para escalar la frecuencia crítica de la región F (foF2) para que se asimilen los cambios ionosféricos relacionados con la tormenta magnética. El modelo provee una poderosa, aunque simple, herramienta para el modelaje de la ionosfera perturbada. La calidad de las predicciones del modelo fue evaluada a través de la comparación con la respuesta ionosférica observada durante las seis mayores tormentas del año 2000. La salida del modelo se comparó con la respuesta ionosférica real en una estación a latitud media (Chilton, coordenadas geográficas: 51.6 N, 358.7 E). Las comparaciones muestran que el modelo captura el decrecimiento de la densidad electrónica particularmente bien para condiciones de verano, y con algo menor calidad para otras condiciones. El valor del modelo fue cuantificado a través de la comparación de la raíz cuadrática del error medio cuadrático (RMSE) de las predicciones de STORM con las de la media mensual. Los resultados de este estudio muestran que el modelo STORM mejora la calidad de la predicción hasta en un 55% respecto a la media mensual para los días de tormentas, una mejora considerable sobre la climatología. El modelo STORM ha sido incluido como la corrección para condiciones magneto perturbadas en la versión más reciente del IRI (International Reference Ionosphere, IRI2000, Bilitza, 2001).

PALABRAS CLAVE: Ionosfera, modelación ionosférica, IRI.

ABSTRACT

Recent theoretical model simulations of the ionospheric response to geomagnetic storms have provided an understanding for the development of an empirical storm-time ionospheric correction model (STORM). The empirical model is driven by the previous time-history of a_p, and is designed to scale the quiet-time F-layer critical frequency (foF2) to account for storm-time changes in the ionosphere. The model provides a useful, yet simple tool for modeling of the perturbed ionosphere. The quality of the model prediction has been evaluated by comparing with the observed ionospheric response during the six biggest storms in 2000. The model output was compared with the actual ionospheric response at a mid-latitude station (Chilton, geographic coordinates: 51.6 N, 358.7 E). The comparisons show the model captures the decreases in electron density particularly well in summer conditions, and with some less quality for other conditions. The value of the model has been quantified by comparing the root mean square error (RMSE) of the STORM predictions with the monthly mean. The results of this study illustrate that the STORM model shows almost a 55 % improvement over the monthly median during the storm days, a significant improvement over climatology. STORM is now included in the latest version of the International Reference Ionosphere (IRI2000, Bilitza, 2001) as the correction for perturbed conditions.

KEY WORDS: ionosphere, ionospheric modeling, IRI.

INTRODUCTION

Understanding the ionospheric response to magnetic perturbations has reached a level where it is possible to develop an empirical model to capture the ionospheric behavior under perturbed conditions. The first characterization of the empirical model was designed to be dependent on the intensity of the storm, and a function of latitude and season (Araujo-Pradere *et al.,* 2001; Fuller-Rowell *et al.,* 1998). The model is based on an analysis of an extensive database of ionosonde observations, guided by simulations using a coupled thermosphere ionosphere model. In this paper we present results from the model for a mid-latitude station (Chilton, 51.6 N, 358.7 E) during six storms in 2000 (April 5, May 23, July 13, August 10, September 15, October 3), and provide a comprehensive validation against available F-region measurements. The main goal is to determine if the empirical model STORM shows a quantitative improvement over the predictions of any quiet reference model, for the conditions here described.

A similar discussion, with a focus in the quality of the STORM prediction for different sites and for a particular storm, can be seen in Araujo-Pradere and Fuller-Rowell, 2001.

The most widely used ionospheric empirical model is the International Reference Ionosphere, IRI, an empirical standard model of the ionosphere, initially based on all available data from 1950 to 1975 and updated periodically. The latest version of the IRI (IRI2000, Bilitza, 2001) includes the STORM model as the correction for perturbed conditions.

OVERVIEW OF THE EMPIRICAL MODEL

The model (Araujo-Pradere *et al.,* 2001) is designed to capture the regional dependence in the development and migration of the storm-driven thermospheric composition disturbance. During a geomagnetic storm Joule and auroral charged-particles heating heats the high latitude region driving a change in the global atmospheric circulation. Upwelling in the auroral regions transports the molecular rich neutral gas from the lower thermosphere to higher altitudes. The composition change, or "bulge," can then be transported horizontally by either the background circulation or the storm driven winds. At solstice, the prevailing circulation from the summer to winter hemisphere is effective in transporting the composition bulge to summer mid and low latitudes (Fuller-Rowell *et al.,* 1996). In the winter hemisphere, this same circulation restricts the movement from the winter polar region to midlatitudes. In fact, the downwelling component of the storm driven circulation depletes the molecular species in the winter midlatitudes (Fuller-Rowell *et al.,* 2001). The neutral composition changes are important for the ionosphere because of the control on electron loss rates.

In order to capture these basic physical processes within an empirical model, data from many storms have been analyzed as a function of season and latitude. The magnitude of the storm-time composition change is dependent on the intensity and time history of the Joule and auroral heating. In the empirical model, the intensity of the response has been quantified by weighting the previous 33 hours of a_p by an appropriate filter shape. The optimum shape and length of the filter was obtained by the singular value decomposition method, minimizing the mean square difference between the filter input (a_p index) and filter output (ionospheric ratios = foF2observed/foF2monthly mean). Detman and Vassiliadis (1997) presented a good discussion of this technique. Including all the features, the algorithm that describes the empirical model is given by Fuller-Rowell *et al.* (1998):

$$\Phi = \{a_0+a_1\, X(t_0)+a_2\, X^2\,(t_0)+a_3\, X^3\,(t_0)\}\ \{1+a_4\, sin\,(LT+\alpha)\}\ , \qquad (1)$$

where Φ = (foF2observed / foF2monthly mean), $X(t_0) = F(\tau)P(t_0\text{-}\tau)d\tau$, and $F(\tau)$ is the filter weighting function of the a_p index, P, over the 33 previous hours. a, b_1, b_2 and b_3 are coefficients adjusted the fit to the non-linear relationship between the ionospheric response and the integral of the geomagnetic index a_p. and are a function of season and latitude.

At this point in the development of the empirical algorithm, the local time dependence represented by coefficient a_4 in Equation 1 has not been included. The analysis by Rodger *et al.* (1989) showed a strong local time signature with a variation of about 40% in NmF2, but we have been unable to show such a strong dependence in the present analysis.

As output, the model provides a Correction Factor (CF) used to scale the IRI or any other quiet-time reference (QT), such as the monthly mean, using the expression:

$$\text{Corrected Value}_{(\text{doy, UT, coord.})}=\text{QT}_{(\text{doy, UT, coord.})}{*}\text{CF}_{(\text{doy, UT, coord.})} \qquad (2)$$

The model is triggered when the filtered a_p exceeds 200 units, i.e.

$$\text{CF}_{\ (\text{doy, UT, coord.})} = 1,\ \text{when}\ X(t_0) = F(\tau)P(t_0\text{-}\tau)d\tau \le 200,$$

which is equivalent to an average a_p of about 9 for the previous time history, or a K_p of 2^+. This avoids making a correction for quiet conditions, for which the model is not designed. For quiet geomagnetic conditions, the use of the monthly mean, the global IRI model, or any other quiet-time reference (CF = 1), is adequate.

The STORM model is currently offered as a semi-operational product of the Space Environment Center (SEC-NOAA). A real time version of the model has been implemented, using the hourly values of the 3-hour running a_p, as provided by the USAF Hourly Magnetometer Analysis Reports. Hourly updates of the model predictions, in six latitude bands, can be found at http://sec.noaa.gov/storm/

DATA SOURCES

The only criterion in the selection of the station was that data were available in the National Geophysical Data Center (NGDC-NOAA) database, and that there was reasonable continuity of the ionospheric data (foF2) for the period of interest. The station selected is Chilton, 51.6 N, 358.7 E, one of the longest working ionospheric stations. The storms were selected under a single criterion: year 2000 (to assure that none of the storms were in the model database) and a_p > 150. Six storms fulfill these conditions, including the well-studied Bastille Day storm of July 2000.

In this work, foF2 hourly values for each site were used for a 5-day period of the storm (120 values), in order to see the full picture of the perturbed period. When higher temporal resolution was available the hourly average was used. The focus of the quantitative analysis will be on the storm-days, when the maximum deviation from the monthly means occurs.

The time history of the geomagnetic index a_p was used as the input of the model. This includes the a_p values for the 33 hours prior to the first hour of the period, which is needed to obtain the first point of the output (due to the length of the filter weighting function). Figure 1 shows the time history of a_p and Dst for the events during 2000. To obtain the foF2 ratio F (foF2 observed / foF2 monthly mean), data for the whole month were used to calculate the monthly mean for each storm. This assures an adequate comparison between the model output (expressed as ratio foF2) and the data. Using just the quiet days for the monthly mean made a small offset to the diurnal curve, but this offset does not affect the results significantly.

RESULTS

The empirical storm-time correction model has been tested for a 5-day period of the storms. Figure 2 shows the response of the ionosphere and the prediction of the empirical model for this station. For each storm, the time evolution of the ratio of the hourly foF2 to the monthly mean foF2 is displayed, together with the prediction of the empirical model. In the quantitative statistical comparisons, we will focus on the days of maximum storm deviation.

The black line represents the ratio in the data, while the thick gray line corresponds to the STORM model output. The x-axis corresponds to time, from 00:00 UT on the first day of the period up to the 120th hour (23:00 UT of the 5th day) of each storm. The y-axis is the ratio of the observed foF2 and the STORM foF2. The value $\Phi = 1$ represents the quiet conditions (monthly mean). Also shown are the normalized RMSE for each 24 hours interval using either the STORM model ratios (empty boxes), or the monthly mean (black crosses) as the prediction. The y-axis also quantifies the RMSE values, the metric used to assess the quality of the predictions. The results presented are from the earlier storm (April 6) to the latest (October 3), covering in this way from equinox to equinox through a solstice and intermediate seasons as defined in Araujo-Pradere *et al.* 2001.

A conclusion from this figure is the ability of the model to capture the tendency of the changes. For non-storm days there are no significant difference between the prediction and the monthly mean RMSE. For storm days, the model well captures the direction and magnitude of the depletion. As given by the RMSE, the quality of the STORM prediction always improves on the monthly mean for the storm days.

Table I shows the numerical values of the Root Mean Square Error (RMSE) for each day of the 5-day period of each storm. In this table the storm days, and the corresponding averages, are shown in bold.

The RMSE for the STORM model shows a consistent improvement over the monthly median (MM) prediction for both the average for the whole period and the average for the storm days. For this particular station, the model shows an average of 55 % improvement over the monthly median during the storm days. We would expect a similar result if a climatological model, such as IRI, was used in place of the monthly mean. There may be small changes in the RMSE since IRI is based on a monthly median rather than mean, but we expect the improvement would be comparable.

While there is a consistent improvement over the monthly mean for all the storms, it is possible to see that the model performance is better during, or around, the summer conditions, when the improvement reach the highest values. This is related with to poor definition of the processes during equinoxes and the complexity for intermediate conditions. Lower values are expected for winter conditions, where the lack of a clear direction to the ionospheric response in winter makes model predictions challenging.

To further expose the quality of the prediction for this storm, Figure 3 shows the average RMSE values corresponding to the storm days, for each of the storms in the study. The x-axis lists the storms, and the y-axis the value of the RMSE for both the model and the monthly mean. Improvements can be seen at all storms, with some less quality of the model prediction for intermediate and equinox conditions (August to October).

CONCLUSION

The quality of the empirical STORM model has been determined by comparing the prediction with the observed ionospheric response for a mid-latitude station during the six biggest storms in 2000. The value of the prediction has been quantified by evaluating the STORM root mean square

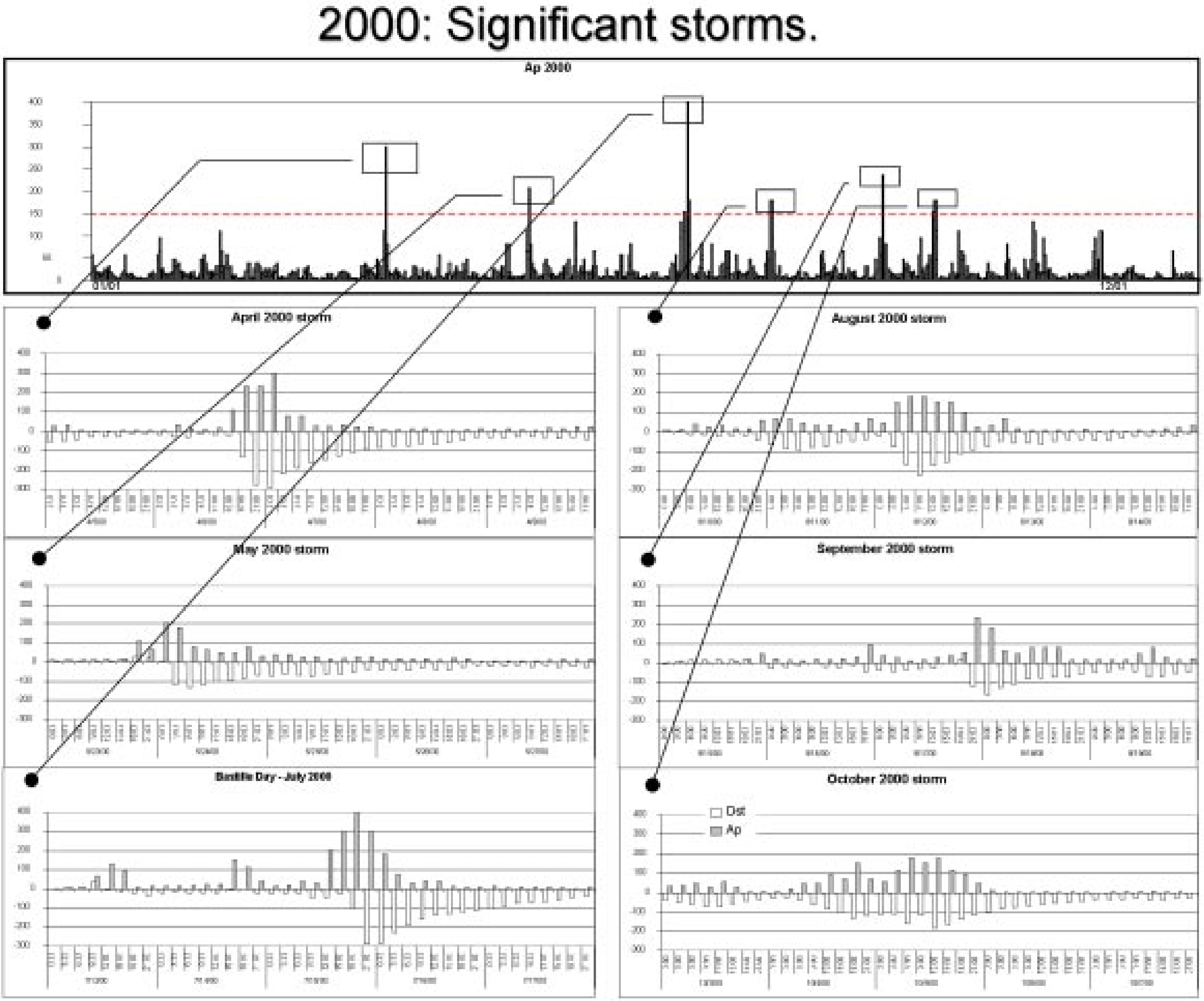

Fig. 1. Geomagnetic activity for the period of interest.

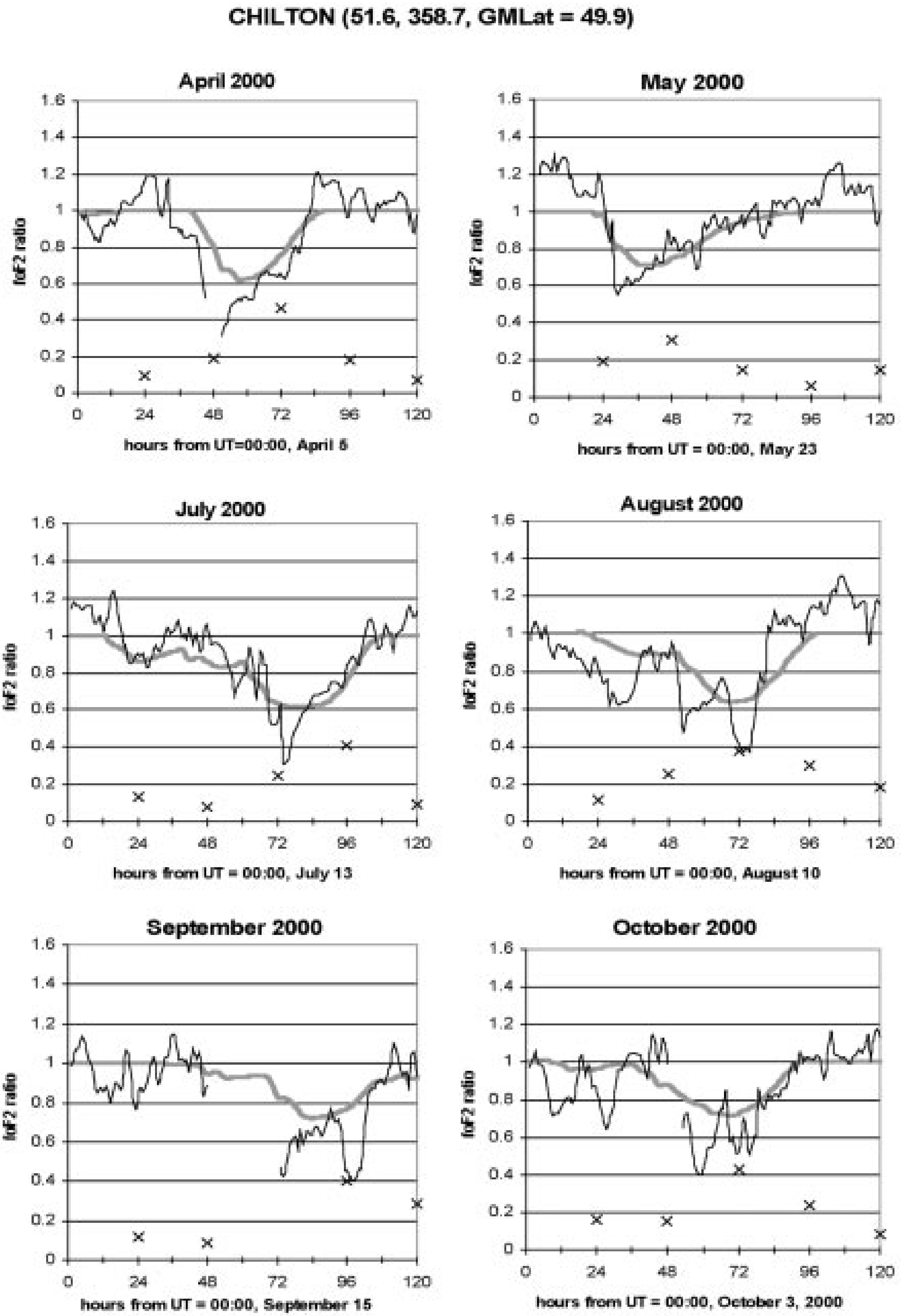

Fig. 2. Data and output of the STORM model for the site and storms of interest.

Table 1

Comparison of the STORM and IRI95 RMSE for all storms.

Apr-00		**May-00**		**Jul-00**		**Aug-00**		**Sep-00**		**Oct-00**	
STORM	IRI	STORM	IRI	STORM	IRI	STORM	IRI	STORM	IRI	STORM	IRI
0.08	0.09	0.20	0.20	0.14	0.13	0.11	0.12	0.12	0.12	0.15	0.16
0.16	0.19	**0.12**	**0.31**	0.10	0.07	**0.19**	**0.26**	0.08	0.09	**0.17**	**0.15**
0.15	**0.46**	**0.07**	**0.15**	**0.11**	**0.25**	**0.16**	**0.38**			**0.21**	**0.43**
0.12	0.18	0.06	0.06	**0.13**	**0.41**	**0.21**	**0.30**	**0.19**	**0.40**	**0.10**	**0.24**
0.07	0.07	0.15	0.15	0.08	0.09	0.18	0.18	0.19	0.28	0.08	0.08
Averages											
0.12	0.20	0.12	0.17	0.11	0.19	0.17	0.25	0.14	0.22	0.14	0.21
Storm-day averages											
0.15	**0.46**	**0.09**	**0.23**	**0.12**	**0.33**	**0.18**	**0.31**	**0.19**	**0.40**	**0.16**	**0.27**
~ % improvement (for storm days)											
68		**60**		**63**		**41**		**53**		**43**	

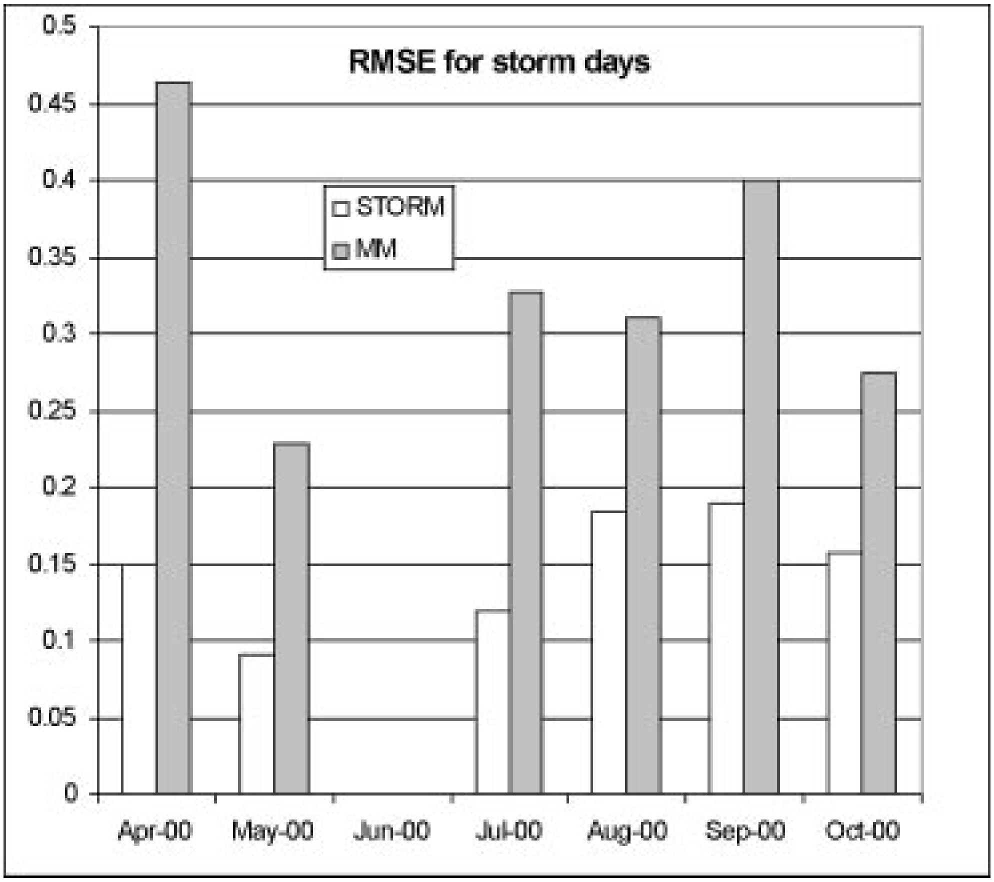

Fig. 3. Storm days average RMSE for each storm.

error (RMSE) and compared with the RMSE from the monthly mean (quiet conditions prediction). The comparison shows that the model captures the decrease in electron density particularly well for summer conditions. For all of the storm days, the model shows almost a 55 % improvement over the monthly median during the storm days, a significant improvement over climatology.

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E. A. Araujo-Pradere
CIRES, University of Colorado and Space Environment Center NOAA
325 Broadway, R/SEC, Boulder, CO 80305, USA
Email: Eduardo.Araujo@noaa.gov