Validation of the STORM model used in IRI with ionosonde data

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Abstract

The empirical ionospheric storm correction model STORM included in the new version of the IRI model is driven by the previous time-history of the ap index and is designed to be dependent on latitude and season. The behavior of this correction model has been analyzed comparing foF2 values obtained by the IRI model with or without storm correction and those measured by ionosondes distributed around the world. A statistical analysis was done using two geomagnetic storms during 2003 (medium solar activity).

Keywords: Ionospheric storm model; IRI; foF2 values; Ionosonde data; Validation

1. Introduction

The International Reference Ionospheric model (IRI) (Bilitza, 1990, 2001) is the result of an international project sponsored by the *Committee on Space Research* (COSPAR) and the *International Union of Radio Science* (URSI), which aims at producing a reference model of the ionosphere based on available experimental data sources. The IRI model can be run on-line at: http://nssdc.gsfc.nasa.gov/space/model/models/iri.html and the source code is available at: ftp://nssdcftp.gsfc.nasa.gov/models/.

One of the major limitations of IRI was that it provided only monthly averages for magnetically quiet conditions. The storm correction model STORM (Araujo-Pradere et al., 2002) was included in the new version of IRI and was designed to be dependent on the intensity of the storm (ap index over the 33 previous hours), latitude, and season. The model considers a threshold of about 9 in the ap index before correcting the foF2 value for quiet conditions. The real time version of the model is available at: http://sec.noaa.gov/storm/.

The purpose of this paper is to evaluate this storm corrections by comparing the foF2 values obtained by the IRI model, with and without storm correction, with those measured by ionosondes. Data from about 15 observing sites have been analyzed for two geomagnetic storms in 2003. Similar validation studies have recently been done by Araujo-Pradere and Fuller-Rowell (2002), Araujo-Pradere et al. (2003, 2004), and Miró Amarante et al. (2004). The results obtained by Araujo-Pradere et al. (2004) show that the storm model captures very well the direction and magnitude of the changes in the summer stations where there is a clear tendency for a negative phase, this was not the case, however, for winter stations likely because of the increased variability in foF2.

2. Data

Table 1 shows the two geomagnetic storms ($ap > 150$) analyzed in this study: October 2003 (smoothed sunspot number: 58.2) and November 2003 (smoothed sunspot number: 56.7). Ionosonde data were obtained directly from several ionospheric groups (National Observatory of

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Table 1
Geomagnetic storm periods selected in the storm model evaluation

Day	Month	Day year	Year	Ap index	Day	Month	Day year	Year	Ap index
27	10	300	2003	11	19	11	323	2003	12
28	10	301	2003	25	20	11	324	2003	150
29	10	302	2003	204	21	11	325	2003	42
30	10	303	2003	191	22	11	326	2003	30
31	10	304	2003	116	23	11	327	2003	22

Athens, Greece; Communications Research Laboratory, Tokyo, Japan; Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy; Instituto de Geofísica y Astronomía, La Habana, Cuba, CASLEO, San Juan, Argentina, and IPS Radio and Space Services, Australia), or downloaded from the University of Massachusetts Lowell DIDBase (http://ulcar.uml.edu/DIDB/DIDBHome.html). In order to avoid possible errors in the automatic scaling those data were manually scaled using the Sao-Explorer software (http://ulcar.uml.edu/SAO-X/SAO-X.html). Ionograms from 30 ionosonde locations were scaled but only those with a continuous 5-day period of foF2 values were included in the evaluation. Geographic coordinates of these observing sites, as well as their geomagnetic latitude and modified dip latitude, are shown in Table 2. Unfortunately, latitudinal dependence cannot be discussed because of the scarcity of high latitude data.

3. Methodology

For each storm hourly measured foF2 values have been compared with model predictions using the IRI with STORM and without STORM. The statistical analysis presented here is based on the method developed by Araujo-Pradere et al. (2004). That paper evaluates the empirical storm-time ionospheric correction model

Table 2
Geographic coordinates, geomagnetic latitudes, and modified dip latitudes of the observing sites used in the storm IRI model evaluation

	Station	Lat.	Long.	Lat. geomag.	Modip
	October 2003				
Midlatitude (40/60)	Fairford (FAI)	51.70	358.50	54.55	56.06
	Chilton (CHI)	51.50	359.40	54.18	55.92
	Rome (ROM)	41.90	12.50	42.40	49.17
	Dyess Afb (DYE)	32.50	260.30	42.16	49.61
Midlatitude (20/40)	Athens (ATH)	38.00	23.50	36.48	45.96
	Wakkanai (WAK)	45.40	141.70	35.42	51.15
	Kokubunji (KOK)	35.70	139.60	25.60	43.44
Low latitude (0/−20)	Jicamarca (JIC)	−12.00	283.20	−0.68	0.65
	Ascension Is (ASC)	−7.95	345.60	−1.40	−23.24
Midlatitude (−20/−40)	Townsville (TOW)	−19.63	146.85	−28.60	−41.26
	Norfolk Is. (NOR)	−29.03	167.97	−34.60	−46.45
	Brisbane (BRI)	−27.53	152.92	−35.58	−46.87
Midlatitude (−40/−60)	Mundaring (MUN)	−31.98	116.22	−43.31	−51.55
	November 2003				
Midlatitude (40/60)	Chilton (CHI)	51.50	359.40	54.18	55.92
	Millstone H (MIL)	42.60	288.50	53.99	55.90
	Rome (ROM)	41.90	12.50	42.40	49.17
	Dyess AFB (DYE)	32.50	260.30	42.16	49.61
	Eglin AFB (EGL)	30.40	273.20	41.23	49.50
	San Vito (SAV)	40.60	17.80	40.11	48.11
Midlatitude (20/40)	Athens (ATH)	38.00	23.50	36.48	45.96
	Wakkanai (WAK)	45.40	141.70	35.42	51.15
	Ramey (RAM)	18.50	292.90	29.89	42.48
	Kokubunji (KOK)	35.70	139.60	25.60	43.44
Low latitude (0/−20)	Ascension Is (ASC)	−7.95	345.60	−1.40	−23.24
Midlatitude (−20/−40)	Concepcion (CON)	−36.80	286.90	−25.42	−35.59
	Townsville (TOW)	−19.63	146.85	−28.60	−41.26
	Learmonth (LEA)	−21.80	114.00	−33.17	−45.14
	Grahamstown (GRA)	−33.30	26.50	−33.80	−50.97
	Norfolk Is. (NOR)	−29.03	167.97	−34.60	−46.45
	Brisbane (BRI)	−27.53	152.92	−35.58	−46.87
Midlatitude (−40/−60)	Mundaring (MUN)	−31.98	116.22	−43.31	−51.55

The ionosonde stations are sorted into three geomagnetic groups (0–20, 20–40, 40–60).

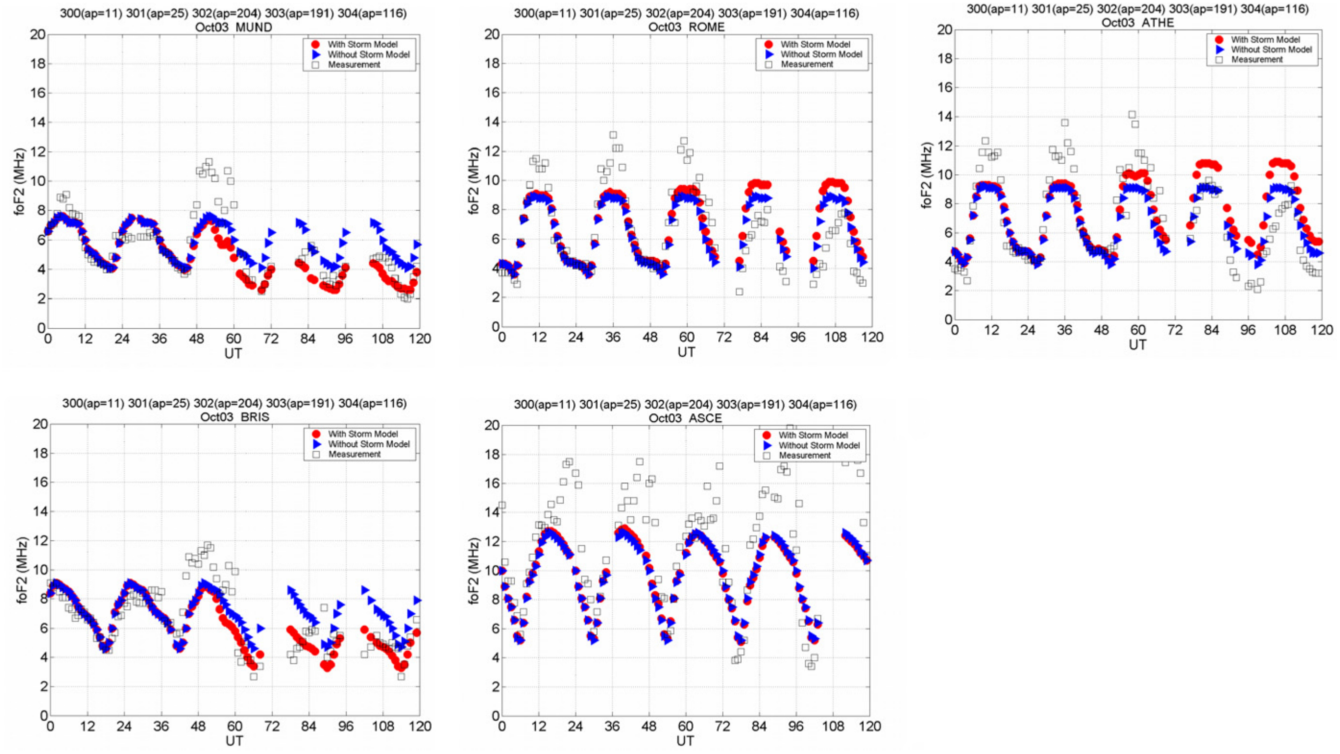

Fig. 1. Hourly variation of foF2 during the October 2003 storm at Mundaring, Rome, Athens, Brisbane, and Ascension Island. Circles, model predictions of foF2 with Storm model; triangles, foF2 predictions without Storm model; squares, foF2 ionosonde values (measurements).

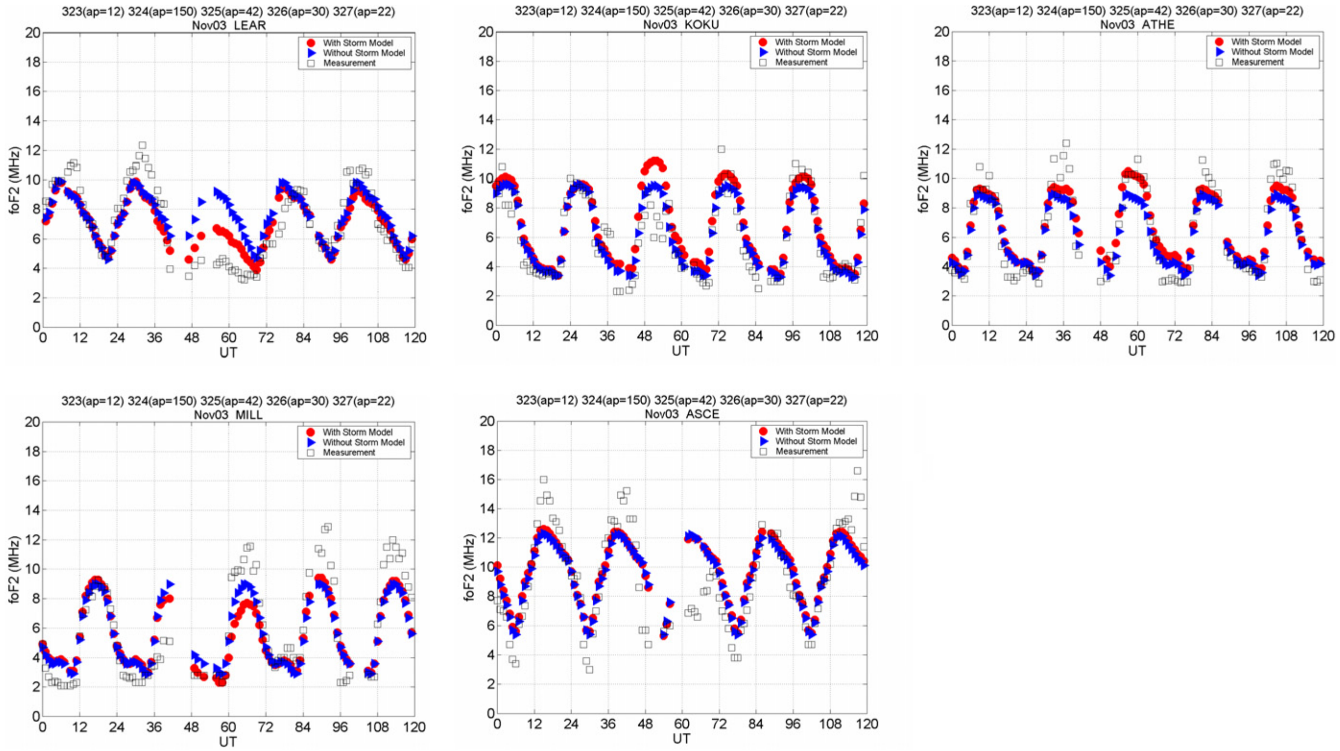

Fig. 2. Hourly variation of foF2 during the November 2003 storm at Learmonth, Kokubunji, Athens, Millstone Hill and Ascension Island. Circles, foF2 values with Storm model; triangles, foF2 predictions without Storm model; squares, foF2 ionosonde values (measurements).

STORM during all the significant geomagnetic storms in 2000 and 2001 (high solar activity). The results obtained in the current study apply to 2003, a middle-low solar activity period, allowing us to establish a possible solar activity dependence of the storm model. We calculated the daily root mean square error (RMSE) for the entire day (RMSE 24 hours), for the period from 08 to 16 LT (RMSE daytime), and for the period from 20 to 04 LT (RMSE nighttime)

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=0}^{N-1} [\mathrm{foF2mod}_i - \mathrm{foF2exp}_i]^2}{N}} \tag{1}$$

were foF2mod is the model prediction and foF2exp the measured value. We calculated RMSE using IRI without STORM and with STORM. N is the number of hours for each case. The percentage improvement (Araujo-Pradere et al., 2004) is then given as

$$\mathrm{improvement}(\%) = \frac{\mathrm{RMSEwithout} - \mathrm{RMSEwith}}{\mathrm{RMSEwithout}} * 100. \tag{2}$$

Negative values of "improvement" indicate that the STORM model is worse than the quiet day model.

4. Results

Fig. 1 compares the measured foF2 values with the model predictions using the Storm and no Storm versions of the IRI model. The plots show the results for some of the stations for a 5-day period (120 h, DOY 300–304) in October 2003. It can be seen that storm effects appear for DOY 302, 303, and 304. The STORM model shows mixed success. For negative ionospheric responses on days 303 and 304 it captures the direction of the changes at Mundaring, Brisbane, Townsville, and Norfolk Is. (summer), as well as at Fairford and Chilton (winter). However, STORM does not capture the direction of the changes at Rome and Athens (winter). For positive ionospheric response on day 302, STORM captures the direction of the changes at Athens, Kokubunji, and Rome (winter), but does not capture the direction of the changes at Brisbane, Mundaring, and Townsville (summer). The STORM model prediction for days 303 and 304 at Ascension Island and Jicamarca (summer) and Dyess and Wakkanai (winter) are not improving the quiet-day IRI predictions.

A similar analysis was made for the November 2003 storm. Fig. 2 shows some examples of the comparison between measured and predicted foF2 values for DOY 323–327 (November 19–23). For the negative ionospheric response on day 325, STORM captures the direction of the changes at Learmonth, Brisbane, Grahamstown, Mundaring, Townsville, Norfolk Is., and Concepcion (summer), but does not capture the direction of the changes at Kokubunji (winter). For the positive ionospheric response, STORM captures the direction of the changes at Athens, Ramey, San Vito and Rome (winter), but does not capture the direction of the changes at Millstone Hill and Chilton

Table 3
Percentage improvement (% Imp) during the 5-day period of the October 2003 (left panel) and November 2003 (right panel) storms at each ionosonde station

October 2003							November 2003							
Name	Lat. geomg	300 % Imp	301 % Imp	302 % Imp	303 % Imp	304 % Imp	Name	Lat. geomg	323 % Imp	324 % Imp	325 % Imp	326 % Imp	327 % Imp
FAI	54.55	3.8	11.7	27.1	50.0	48.9	CHI	54.18	−1.3	2.1	−100.0	4.3	−7.3
CHI	54.18		10.9	26.7	45.6	40.7	MIL	53.99	−11.5	9.5	−52.9	10.1	4.5
ROM	42.40	6.8	9.0	17.3	−41.2	−37.1	ROM	42.40	5.2	8.0	9.6	6.5	24.2
DYE	42.16	3.6	10.7	−2.4	−1.4	−2.7	DYE	42.16	0.0	−4.8	−0.3	15.2	15.3
ATH	36.48	3.4	8.9	22.6	−108.2	−70.8	EGL	41.23	5.6	−4.8	−2.6	12.0	15.0
WAK	35.42	4.3	9.7	4.0	−1.8	0.0	SAV	40.11	2.5	8.9	5.1	3.4	13.0
KOK	25.60	2.2	4.3	15.5	−29.4	27.5	ATH	36.48	2.0	15.0	13.4	−2.2	19.5
JIC	−0.68	2.6	5.1	2.8	−0.5	−10.0	WAK	35.42	−11.7	−10.3	−7.0	−34.2	0.0
ASC	−1.40	1.9	3.0	1.0	−3.3	−2.5	RAM	29.89	10.0	17.9	13.2	16.0	20.1
TOW	−28.60	0.0	−1.0	−23.5	50.7	16.1	KOK	25.60	−15.9	−27.6	−66.7	−7.5	5.1
NOR	−34.60	0.0	−4.4	−8.1	61.5	48.0	ASC	−1.40	0.0	2.6	1.8	−11.6	6.3
BRI	−35.58	−1.6	−1.2	−6.4	38.3	63.4	CON	−25.42	−0.5	28.7	28.8	−4.9	2.6
MUN	−43.31	0.0	−2.5	−15.6	39.4	59.9	TOW	−28.60	−0.7	11.7	58.6	−13.8	−16.5
							LEA	−33.17	−1.0	1.2	51.9	17.5	−8.8
							GRA	−33.80	−2.2	10.9	58.8	9.0	24.3
							NOR	−34.60	−1.6	36.6	54.4	−38.0	−7.0
							BRI	−35.58	0.9	28.2	46.0	−17.8	−12.0
							MUN	−43.31	0.0	15.2	73.9	−6.3	11.1

(winter). STORM does not improve the predictions on day 325 at Ascension Island (summer), Wakkanai, Dyess, and Eglin (winter).

Clearly, STORM does not improve the predictions the two low latitude stations analyzed, Ascension Island and Jicamarca, during the storm periods. This is to be expected because of the scarcity of data that were available for the development of STORM and the still poor understanding of the different low latitude physical processes involved (Araujo-Pradere et al., 2002).

Table 3 shows the percentage improvements, as defined above for the 5-day storm periods in October (left panel) and November (right panel) 2003. The RMSE was calculated considering the previous 24 h. Table 3 is sorted by geomagnetic latitude since the STORM model was designed with a latitudinal dependence. Negative values

Table 4
RMSE for Northern and Southern Hemispheres for each of the 5 days in October 2003 storm

Day	Ap	RMSE 24 hours			RMSE daytime			RMSE nighttime		
		Count	Storm	No Storm	Count	Storm	No Storm	Count	Storm	No storm
North hemisphere (Oct 2003)										
300	11	142	1.34	1.39	52	1.81	1.89	54	0.62	0.64
301	25	165	1.36	1.50	61	2.06	2.28	62	0.51	0.56
302	204	139	**1.70**	**2.02**	56	**2.26**	**2.71**	48	**1.12**	**1.30**
303	191	123	**2.90**	**2.91**	55	**2.18**	**2.20**	34	**4.18**	**4.15**
304	116	154	**2.02**	**1.94**	62	**2.45**	**2.34**	52	**1.86**	**1.82**
Average storm period			1.86	1.95		2.15	2.28		1.66	1.69
Average storm days			**2.21**	**2.29**		**2.30**	**2.42**		**2.39**	**2.42**
% improvement			**3.5%**			**4.9 %**			**1.2%**	
South hemisphere (Oct 2003)										
300	11	135	1.52	1.55	51	1.37	1.42	52	1.75	1.76
301	25	131	1.96	2.01	48	1.74	1.82	47	2.18	2.21
302	204	108	**2.38**	**2.25**	41	**2.20**	**2.05**	42	**2.69**	**2.62**
303	191	97	**2.09**	**2.58**	19	**2.31**	**2.77**	45	**2.02**	**2.26**
304	116	105	**2.00**	**2.46**	21	**2.39**	**2.99**	52	**1.79**	**2.04**
Average storm period			1.99	2.17		2.00	2.21		2.09	2.18
Average storm days			**2.16**	**2.43**		**2.30**	**2.60**		**2.17**	**2.31**
% improvement			**11.1%**			**11.5%**			**6.1%**	

Averages for the entire storm period and for the specific storm days (in bold) are also shown. The percentage of improvement is calculated for the storm days. Results are also shown for daytime (08–16 LT) and nighttime (20–04 LT).

Table 5
RMSE for North and South Hemispheres for each of the 5 days in November 2003

Day	Ap	RMSE 24 hours			RMSE daytime			RMSE nighttime		
		Count	Storm	No storm	Count	Storm	No storm	Count	Storm	No storm
North hemisphere (Nov 2003)										
323	12	237	0.86	0.85	89	0.86	0.94	88	0.82	0.75
324	150	203	**1.97**	**2.13**	82	**2.37**	**2.63**	66	**0.95**	**0.88**
325	42	213	**2.43**	**2.38**	81	**2.35**	**2.02**	80	**3.06**	**3.16**
326	30	202	1.17	1.26	73	1.51	1.73	76	0.75	0.66
327	22	214	1.23	1.40	90	1.42	1.74	67	1.01	0.98
Average storm period			1.53	1.60		1.70	1.81		1.32	1.29
Average storm days			**2.20**	**2.26**		**2.36**	**2.32**		**2.00**	**2.02**
% improvement			**2.6%**			**−1.7%**			**1.0%**	
South hemisphere (Nov 2003)										
323	12	179	1.31	1.30	64	1.27	1.26	71	1.37	1.36
324	150	161	**1.54**	**1.89**	63	**1.52**	**1.93**	59	**1.40**	**1.61**
325	42	107	**1.79**	**2.80**	16	**2.93**	**4.02**	57	**1.56**	**2.52**
326	30	146	1.36	1.28	55	1.45	1.34	52	1.36	1.31
327	22	161	1.28	1.28	61	1.53	1.46	61	1.14	1.22
Average storm period			1.46	1.71		1.74	2.00		1.37	1.60
Average storm days			**1.66**	**2.34**		**2.22**	**2.97**		**1.48**	**2.06**
% improvement			**29.0%**			**25.2%**			**28.1%**	

Averages for the entire storm period and for the specific storm days (in bold) are also shown. The percentage improvement is calculated for the storm days. Results are also shown for daytime (08–16 LT) and nighttime (20–04 LT).

mean that STORM worsens the predictions (shadowed cells).

The predicted values for the negative effects observed in the Australian region and at two European stations (Chilton and Fairford) during October 2003 (days 303 and 304) are improved by up to 63%. In the case of November 2003 (day 325), the improvement reaches values of 74% in the Australian region. It is important to point out that Chilton and the Australian stations have been included in the 75 ionosonde stations used in the development of the STORM model (Araujo-Pradere et al., 2002). The model improvement is moderate for positive effects predictions, up to 23% in October 2003 and 13% in November 2003, both of them in Athens station.

Table 4 shows the RMSE for the Northern and Southern Hemispheres for each of the 5 days in October 2003. Storm days are marker in bold. The average for the entire storm period and for the specific storm days (bold) are also shown. The percentage of improvement is calculated for the storm days. As it has been noticed before, the best results are found for the Southern Hemisphere (summer stations) where the percentage improvement is more than 10%. In order to find a possible hourly dependence, RMSE and the percentage improvement has been separately calculated for day- and nighttime periods. The results obtained clearly show that the model works better between 08:00 and 16:00 LT.

The analysis results for the November 2003 storm are shown in Table 5. In this case, the STORM model improves the predictions up to 29% for summer stations. For this particular storm, results do not show differences between daytime and nighttime behavior.

The percentages of improvement found by Araujo-Pradere et al. (2004) for October and November 2001 storms are calculated with the previous 24 h and in general, they are larger than the corresponding values obtained in this paper. These differences could be related to the higher solar activity in 2001, the sunspot number was around 115, double that in 2003.

5. Conclusions

Two geomagnetic storms (ap > 150) have been analyzed: October 2003 (13 ionosonde stations; smoothed sunspot number: 58.2), and November 2003 (18 ionosonde stations; smoothed sunspot number: 56.7). Measured foF2 data were compared with IRI model predictions using the STORM or no-STORM versions. STORM captures quite well the direction of the changes for negative effects during summer conditions. The improvement reaches values up to 63% during October 2003 and 74% for November 2003. For positive effects during winter conditions STORM, in general, improves the predictions in Europe and Japan with improvements reaching 23% for October 2003 and 13% for November 2003. For low latitudes (Ascension Island and Jicamarca) no clear improvement is achieved. In the case of the October 2003 storm the model works better during daytime with improvement of 11% at southern locations.

Further studies including high latitude data are required to establish a possible latitudinal dependence of the accuracy in foF2 predictions.

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