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An evaluation of the IRI-2007 storm time model at low latitude stations

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Abstract

This paper discusses the ability of the International Reference Ionosphere IRI-2007 storm time model to predict *foF2* ionospheric parameter during geomagnetic storm periods. Experimental data (based on availability) from two low latitude stations: Vanimo (geographic coordinates, 2.7 °S, 141.3 °E, magnetic coordinates, 12.3 °S, 212.50 °E) and Darwin (geographic coordinates, 12.45 °S, 130.95 °E, magnetic coordinates, 22.9 °S, 202.7 °E) during nine storms that occurred in 2000 ($Rz_{12} = 119$), 2001($Rz_{12} = 111$) and 2003 ($Rz_{12} = 64$) are compared with those obtained by the IRI-2007 storm model. The results obtained show that the percentage deviation between the experimental and IRI predicted *foF2* values during these storm periods is as high as 100% during the main and recovery phases. Based on the values of "relative deviation module mean" (RDMM) obtained (i.e. between 0.08 and 0.60), it is observed that there is a reasonable to poor agreement between measured *foF2* values and the IRI-storm model prediction values during main and recovery phases of the storms under investigation. As a result, in addition to other studies that have been carried out from different sectors, more studies are required to be carried out. This will enable IRI community to improve on the present performance of the model. In general the IRI-storm model predictions follow normal trend of the *foF2* measured values but does not reproduce well the measured values.

Keywords: *foF2*; IRI; Geomagnetic storm; Equatorial ionosphere

1. Introduction

Ionospheric storms, associated with geomagnetic storms, which are driven by highly variable solar and magnetospheric energy inputs to the Earth's upper atmosphere represent an extreme form of space weather that can have large effects on the regular structure of the ionosphere which in turn can lead to adverse effects on ground and space based communication and navigation systems (Titheridge and Buonsanto, 1988; Buonsanto, 1999).

The critical frequency (*foF2*) value is an important ionospheric parameter in the study of ionospheric radio-wave propagations. This parameter which is related to the peak electron density (*NmF2*) of the F2- region is either increased or decreased during geomagnetic storm periods.

An increase in the electron density as a result of ionospheric storm is known as positive ionospheric storm (or positive phase), while a decrease in the electron density is called a negative ionospheric storm (or negative phase) (Danilov and Morozova, 1985; Prölss, 1993; Werner et al, 1999).

Several studies by many researchers have shown that the effects of ionospheric storms on the ionosphere depend on the season, intensity of the storm, local time and location (latitude, longitude and altitude) (Titheridge and Buonsanto 1988; Essex et al.,1981; Schödel et al., 2001; Araujo-Pradere et al., 2002a; Araujo-Pradere and Fuller-Rowell, 2002b; Adewale et al., 2010). Batista et al. (1991) in their studies of magnetic storm of 13–14 March 1989 at an equatorial station, Fortaleza (3.55 °S, 38.25 °W), found large negative phase in *foF2*. Also, Basu et al. (2001) in their studies of the great magnetic storm of July 15, 2000 at two equatorial ionospheric stations (Ascension Island, 7.9 °S, 12.4 °E and Fortaleza, 3.55 °S, 38.25 °W) observed

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Table 1
Storm dates, Rz_{12} and minimum Dst used in the study.

Year	Date	Rz_{12}	Minimum Dst (nT)
2000	5–8 April	119	−288
	15–17 July		−301
	3–6 October		−182
2001	30 March–2 April	111	−358
	10–13 April		−256
	21–24 October		−166
2003	17–20 August	64	−168
	28–31 October		−401
	19–22 November		−472

large westward plasma drift in the evening equatorial ionosphere due to ionospheric disturbance dynamo. As a result the IMF Bz component turned southward and caused penetration of E-fields to low latitudes. Several researchers (Basu et al., 1996; Buonsanto, 1999; Fejer et al., 1999; Danilov, 2001) have reported the complex variations of the electric fields, plasma drifts and the onset of plasma instabilities in the equatorial F-region during intense geomagnetic storm periods. It was suggested that possible causes of this complexity are due to variable nature of coupling between high and low latitudes arising from solar wind magnetospheric dynamo (i.e. changes in the polar cap potential that causes prompt penetration of electric field to low latitudes) (Spiro et al., 1988; Fejer and Scherliess, 1997) and the ionospheric disturbance dynamo arising from changes in the global circulation induced by Joule heating at aurora latitudes during ionospheric storms (Blanc and Richmond, 1980; Scherliess and Fejer, 1997).

A large number of models (empirical and semi-empirical) have been developed over the years mainly for ionospheric predictions during magnetically quiet conditions (Bent et al., 1976; Anderson et al., 1987; Bilitza 1986, 2001). Out of these models, the International Reference Ionosphere (IRI) model (Bilitza 1986, 2001) is the most widely used for ionospheric predictions. A storm-time ionospheric correction (STORM model) developed by Fuller-Rowell et al. (2000) was included in the IRI model. This development makes the IRI model to have two versions (i.e. STORM-on model and STORM-off model).

In view of these complexities, the abilities of the IRI model to predict ionospheric parameters have been studied by many researchers (Batista et al., 1991; Adeniyi et al., 2003; Araujo-Pradere and Fuller-Rowell, 2003; Araujo-Pradere et al., 2004; Sethi et al., 2004; Batista and Abdu, 2004; Bertoni et al., 2006; MiroAmarante et al., 2007; Mansilla and Mosert, 2007; Adewale et al., 2009; Oyeyemi and Adewale, 2009). These results have shown improvement of the IRI model predictions of ionospheric parameters in the recent years.

In this paper, we evaluated the ability of the IRI-2007 storm time model to predict *foF2* ionospheric parameter from two low latitude stations: Vanimo (geographic coordinates, 2.7 °S, 141.3 °E, magnetic coordinates, 12.3 °S, 212.50 °E) and Darwin (geographic coordinates, 12.45 °S, 130.95 °E, magnetic coordinates, 22.9 °S, 202.7 °E) by comparing the *foF2* measured values with those obtained by the IRI-2007 storm model. We have used data from nine geomagnetic storms (peak $Dst < -100$ nT) occurring in the years 2000 ($Rz_{12} = 119$), 2001($Rz_{12} = 111$) and 2003 ($Rz_{12} = 64$).

2. Data and methodology

Data used for this study are monthly median and hourly values of *foF2* measured ionospheric parameter of the F2-region for two low latitude stations Vanimo (2.7 °S, 141.3 °E) and Darwin (12.45 °S, 130.95 °E) during nine geomagnetic storms occurring in the years 2000, 2001 and 2003. The selection of these storm periods were based on the availability of data from these stations. The *foF2* measured values were obtained through the World Data Center (WDC) database of the Space Physics Interactive Data Resource, SPIDR (http://spidr.ngdc.noaa.gov/). The monthly averaged values of *foF2* for the IRI with the STORM model turned on were obtained through http://omniweb.gsfc.nasa.gov/vitmo/iri_vitmo.htm.

The Dst and Ap indices have been used as indicators of geomagnetic activity. Hourly Dst and 3-hourly Ap indices were also obtained from Space Physics Interactive Data Resource, SPIDR (http://spidr.ngdc.noaa.gov/). Table 1 below shows a list of the nine selected geomagnetic storms used in this study.

In order to quantify the degree of agreement/disagreement between the experimental values and the predicted values by the IRI model, we have used a criterion called "relative deviation module mean" (thereafter referred to as RDMM) (Bertoni et al. (2006)). The RDMM is obtained according to the following expression:

$$\mathrm{RDMM}, \langle\Delta\rangle = \frac{1}{N}\sum_{i=1}^{N}\frac{|X_{ei} - X_{mi}|}{X_{ei}} \quad (1)$$

where X_{ei} and X_{mi} are the experimental and IRI model prediction values respectively, and N is the number of data points. A model exhibits a reasonable to good agreement with the experimental values when the RDMM is less than or equal to 0.06 and a reasonable to poor agreement when RDMM is higher than 0.06.

Also, the percentage deviation between the IRI-model prediction values was evaluated using the equation

$$\%\ \mathrm{Deviation} = \frac{X_{ei} - X_{mi}}{X_{mi}} \times 100 \quad (2)$$

and X_{ei} and X_{mi} have their usual meanings.

3. Results

Figs. 1–9 show from the top, the Dst geomagnetic index, Ap geomagnetic index, measured *foF2* (storm time and monthly averaged of measured *foF2* data) and output of

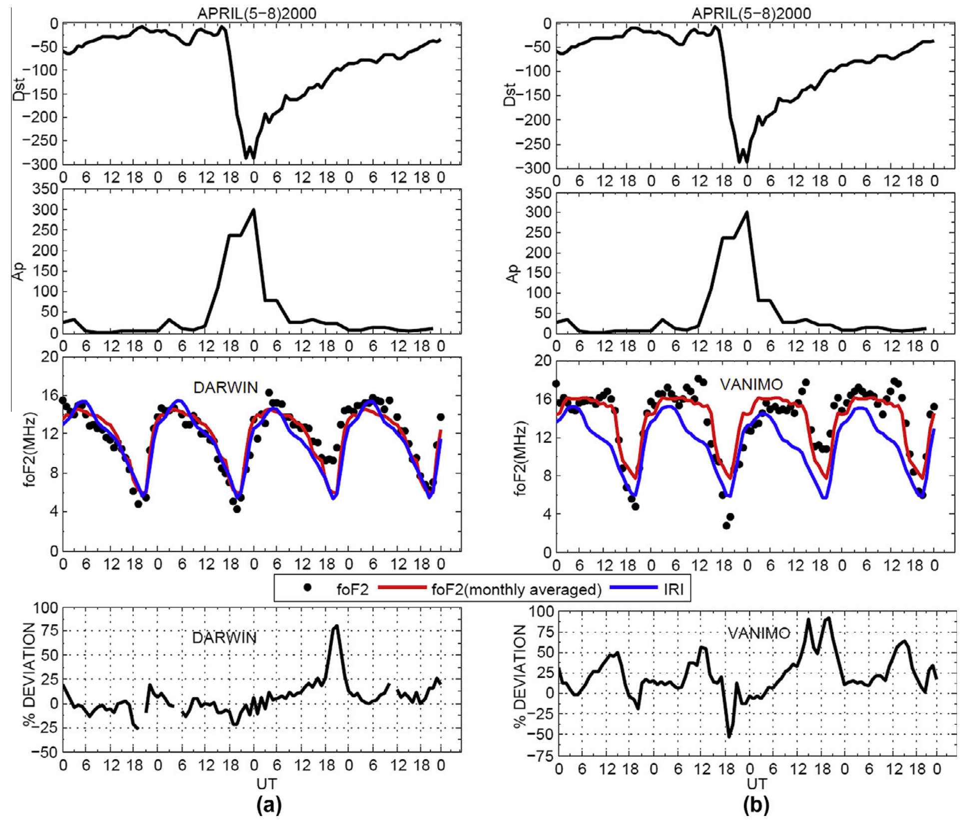

Fig. 1. Variation of Dst index (upper panel), Ap index (second from top panel), storm time *foF2* (solid black circles), monthly averaged *foF2* (red sold line), IRI STORM model predictions (solid blue line) and percentage deviation (lower panel) for the storm period 5–8 April 2000, (a) at Darwin ionospheric station and (b) at Vanimo ionospheric satiation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the IRI-2007 model with storm model, and percentage deviation for IRI from measured *foF2* values for the period of the storm considered in each case for Darwin station (Figs. 1a–9a) and Vanimo (Figs. 1b–9b).

From each of Figs. 1–9, it can be observed that there is a significant increase in the Ap index which occurred simultaneously at the maximum negative excursion of the Dst index. The second panel from the bottom in each figure shows a comparison of the diurnal behaviour of measured *foF2* storm time data (solid black circles) with monthly averaged measured *foF2* (solid red line) and the predictions by IRI-2007 with the storm model included (solid blue line) over Darwin and Vanimo stations during each storm period considered. From the available data it is evident that IRI-2007 model predictions follow the variation of the *foF2* measured data but does not reproduce well the measured data. There are cases where IRI significantly overestimates measured data from the two stations (Figs. 3, 8 and 9) and cases where IRI underestimates [i.e. Vanimo (Fig. 1b (5–8) April 2000, 2b (15–17) July 2000, 4b (1 April–2 April) 2001, 5b (10–13) April 2001, 7b (18 and 20 August) 2003) and Darwin (Fig. 4a (1 April) 2001, 7a (20 April) 2003)] during main and recovery phases.

A closer inspection of Figs. 1–9 show that sudden commencement (SC) occurs at different times of the day in each storm period. For instance, in Fig. 1, sudden commencement (SC) for 5–8 April 2000 storm period occurred around 16–17 UT (01:00–02:00 LT) (LT = UT + 9.30 h for Darwin and LT = UT + 9:20 h for Vanimo) on 6 April 2000 with a maximum negative excursion of Dst = −288 nT around 00:00 UT on 7 April before a fast recovery phase. A similar period of occurrence of SC occurred for storm periods of 15–17 July 2000 on 15 July (Fig. 2), 10–13 April 2001 on 11 April (Fig. 5), 21–24 October 2001 on 21 October (Fig. 6) around 16–17 UT with their corresponding maximum negative excursion as given in Table 1.

The SC of 3–6 October 2000 storm period occurred during the sunrise hour around 22 UT (07LT) on October 4, 2000 (Fig. 3). A different case is observed during 30 March–2 April 2001 storm period where SC occurred near local noon 02 UT (11 LT) at these stations (Fig. 4).

Generally, IRI predictions underestimate the experimental *foF2* values at Vanimo station than Darwin station. This can be observed during the storm periods as shown in Figs. 1, 2, 4, 5 and 7b. Overestimation of the measured data by the IRI model only occurred during the storm periods of 28–31 October 2003 and 19–22 November 2003 (Figs. 8 and 9b respectively). This significant difference between measured and IRI model prediction values may

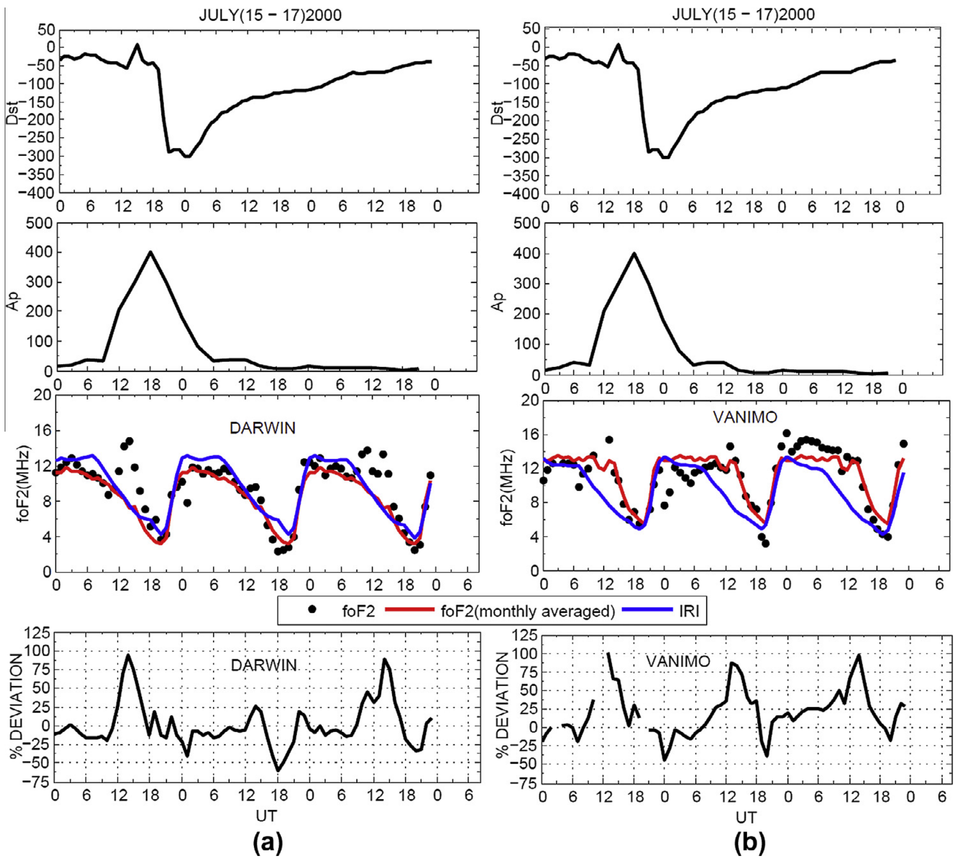

Fig. 2. Same as Fig. 1, but for storm period 15–17 July 2000.

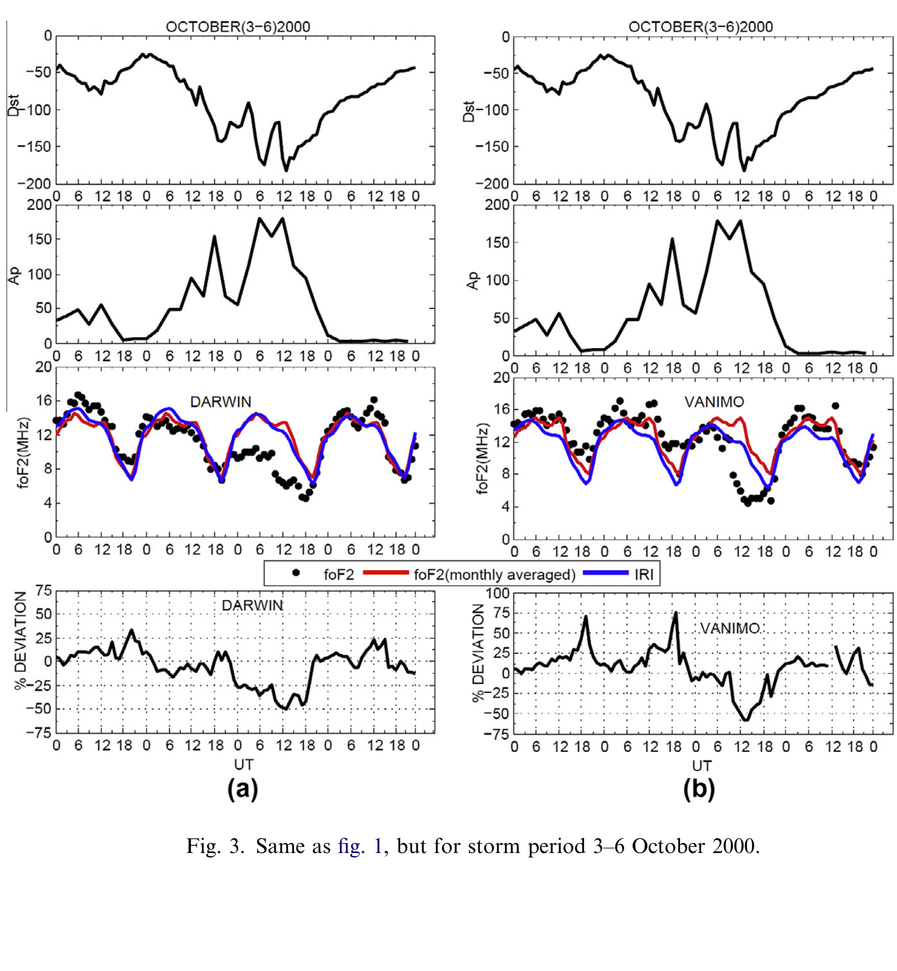

Fig. 3. Same as fig. 1, but for storm period 3–6 October 2000.

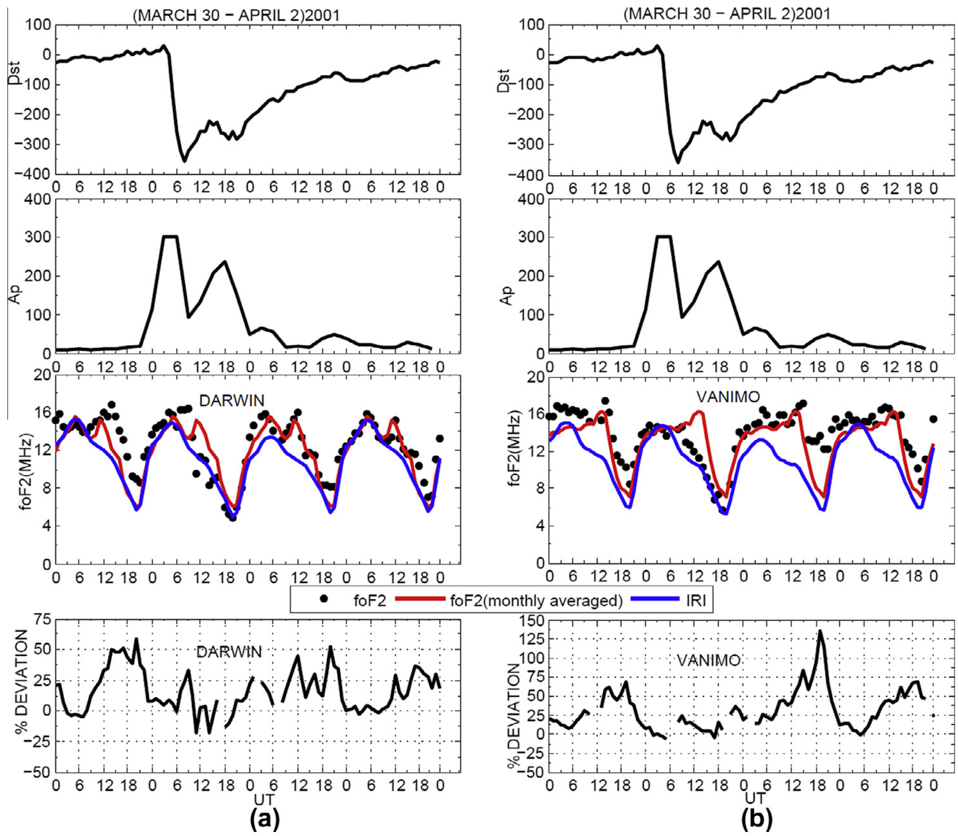

Fig. 4. Same as Fig. 1, but for storm period 30 March–2 April 2001.

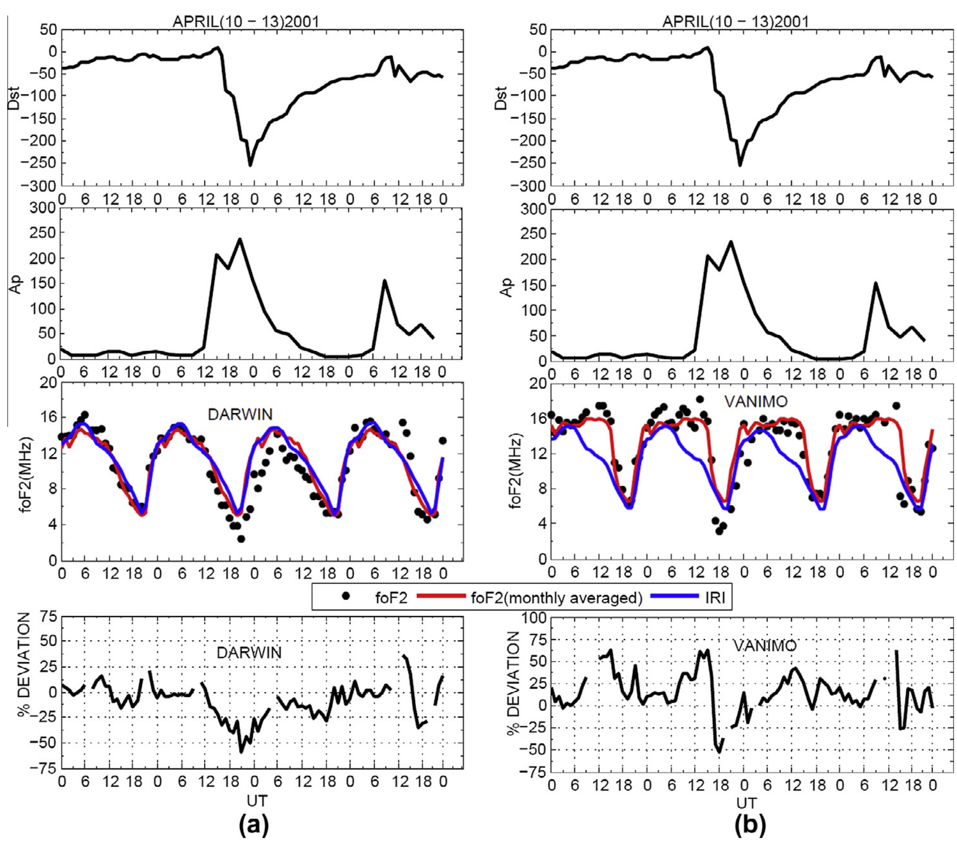

Fig. 5. Same as Fig. 1, but for storm period 10–13 April 2001.

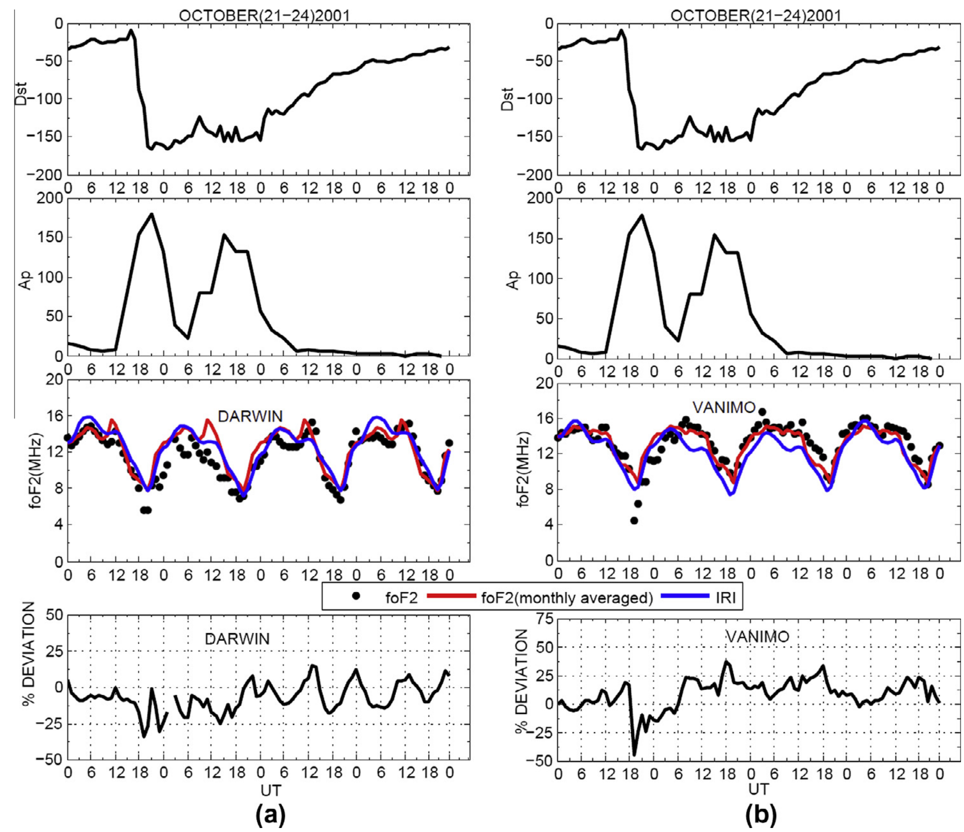

Fig. 6. Same as Fig. 1, but for storm period 21–24 October 2001.

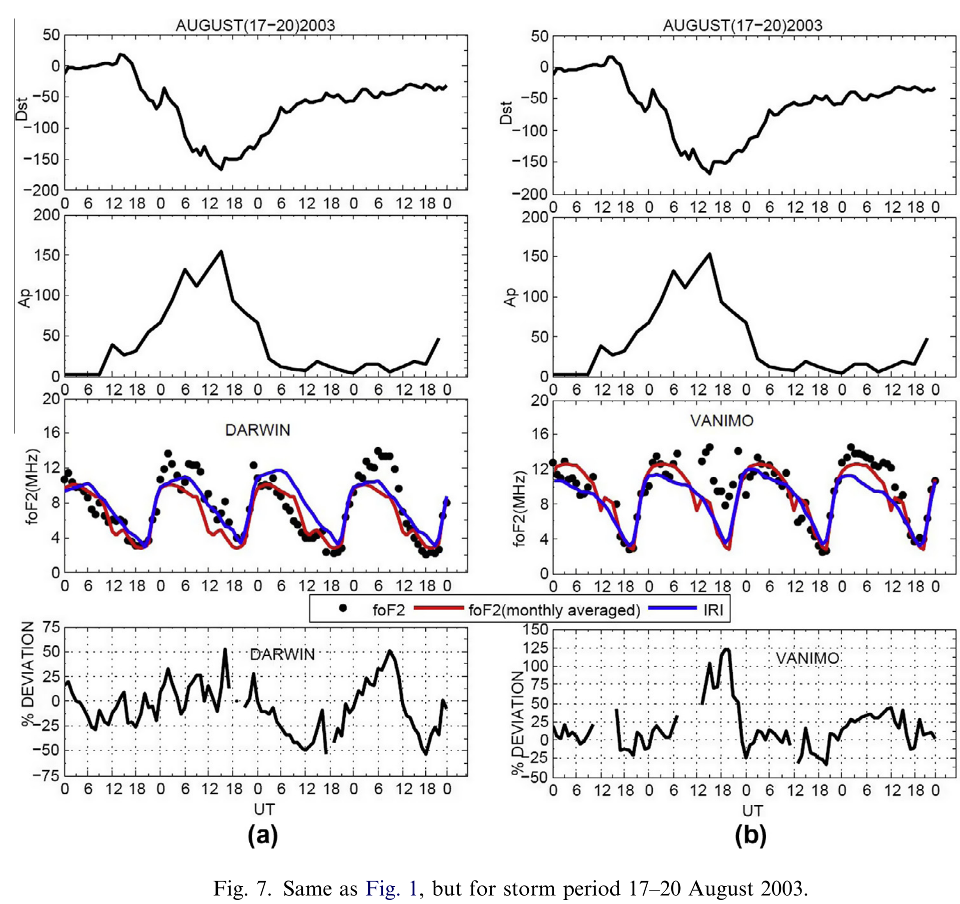

Fig. 7. Same as Fig. 1, but for storm period 17–20 August 2003.

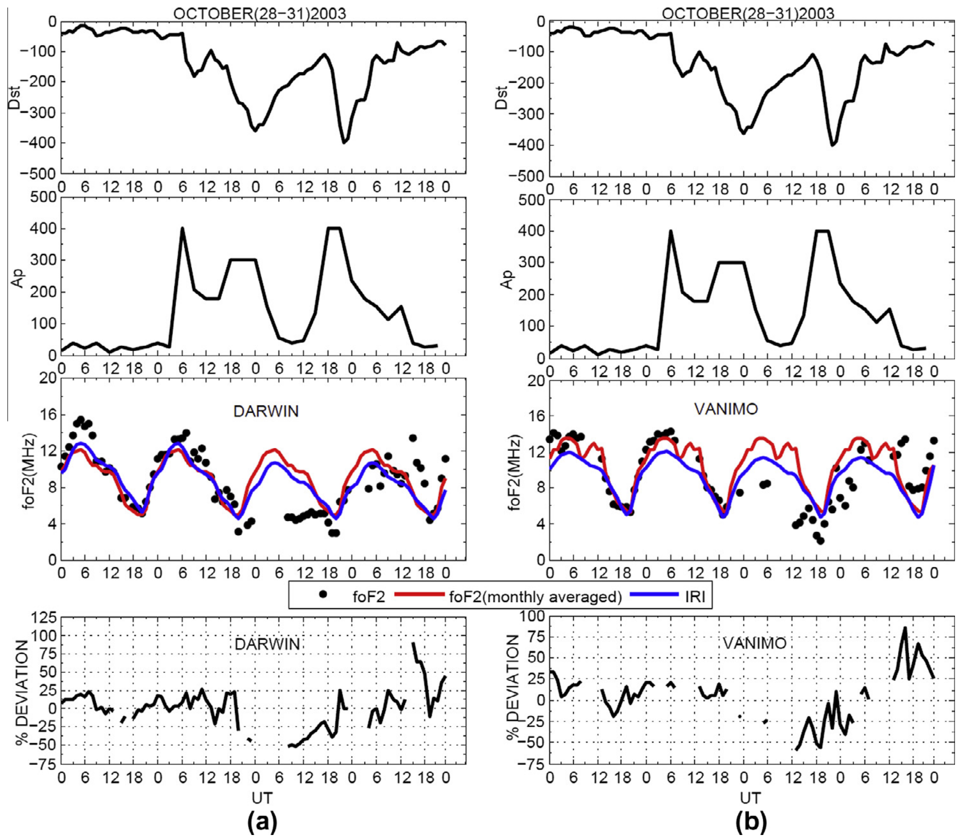

Fig. 8. Same as Fig. 1, but for storm period 28–31 October 2003.

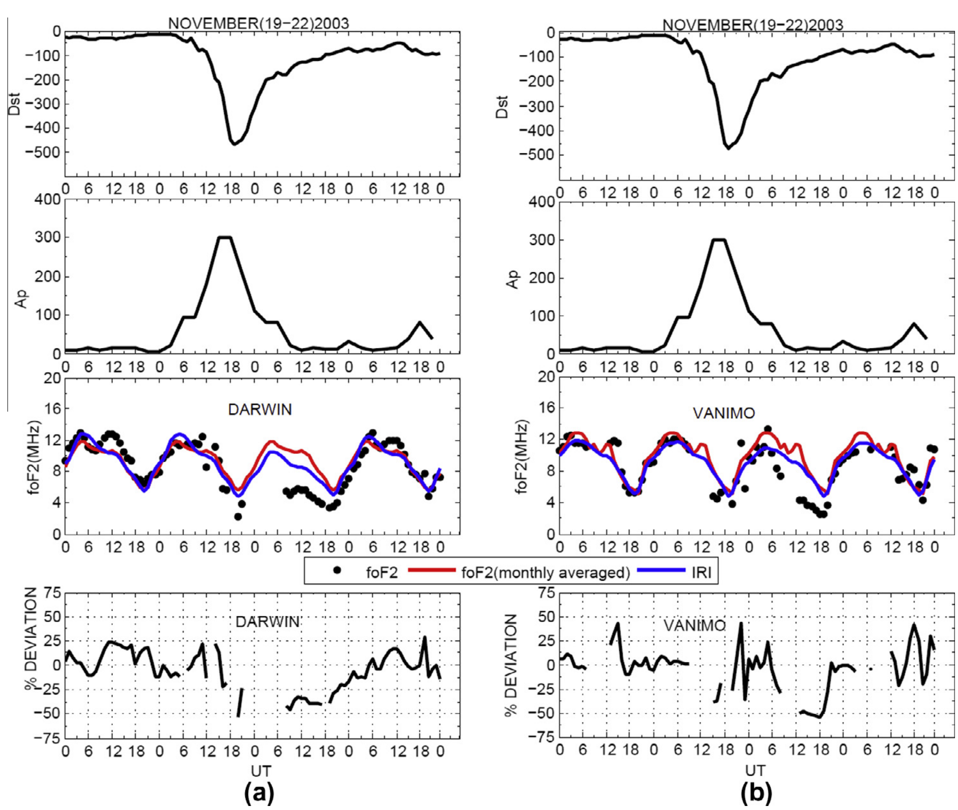

Fig. 9. Same as Fig. 1, but for storm period 19–22 November 2003.

Table 2a
Values of RDMM for all days of the storm periods considered at Darwin (bold font refers to maximum RDMM).

Darwin 2000					
April		July		October	
Date	RDMM	Date	RDMM	Date	RDMM
5	0.09	15	0.18	3	0.10
6	0.08	16	**0.29**	4	0.09
7	**0.16**	17	0.20	5	**0.47**
8	0.08			6	0.09
2001					
March/April		April		October	
30	0.18	10	0.08	21	0.13
31	0.10	11	**0.30**	22	**0.16**
1	**0.18**	12	0.21	23	0.09
2	0.11	13	0.14	24	0.08
2003					
August		October		November	
17	0.16	28	0.09	19	0.11
18	0.13	29	0.18	20	0.19
19	**0.45**	30	**0.53**	21	**0.54**
20	0.30	31	0.19	22	0.09

Table 2b
Values of RDMM for all days of the storm periods considered at Vanimo (bold font refers to maximum RDMM).

Vanimo 2000					
April		July		October	
Date	RDMM	Date	RDMM	Date	RDMM
5	0.16	15	0.15	3	0.14
6	0.22	16	**0.25**	4	0.15
7	**0.24**	17	0.22	5	**0.35**
8	0.19			6	0.12
2001					
March/April		April		October	
30	0.22	10	0.16	21	0.11
31	0.1	11	**0.28**	22	**0.14**
1	**0.31**	12	0.15	**23**	0.13
2	0.22	13	0.14	24	0.08
2003					
August		October		November	
17	0.12	28	0.12	19	0.08
18	**0.29**	29	0.12	20	0.18
19	0.16	**30**	**0.60**	**21**	**0.45**
20	0.18	31	0.29	22	0.13

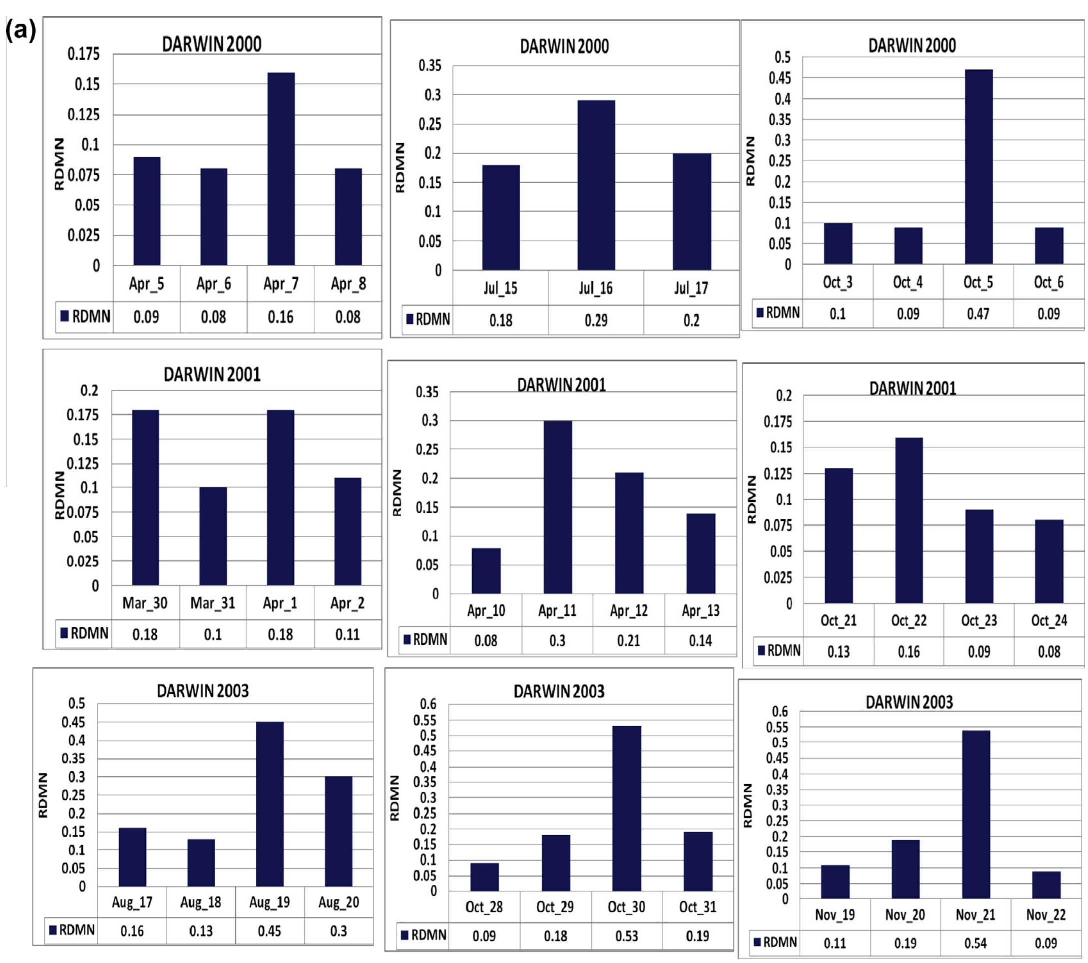

Fig. 10a. Bar graph representation of RDMM values for Darwin station.

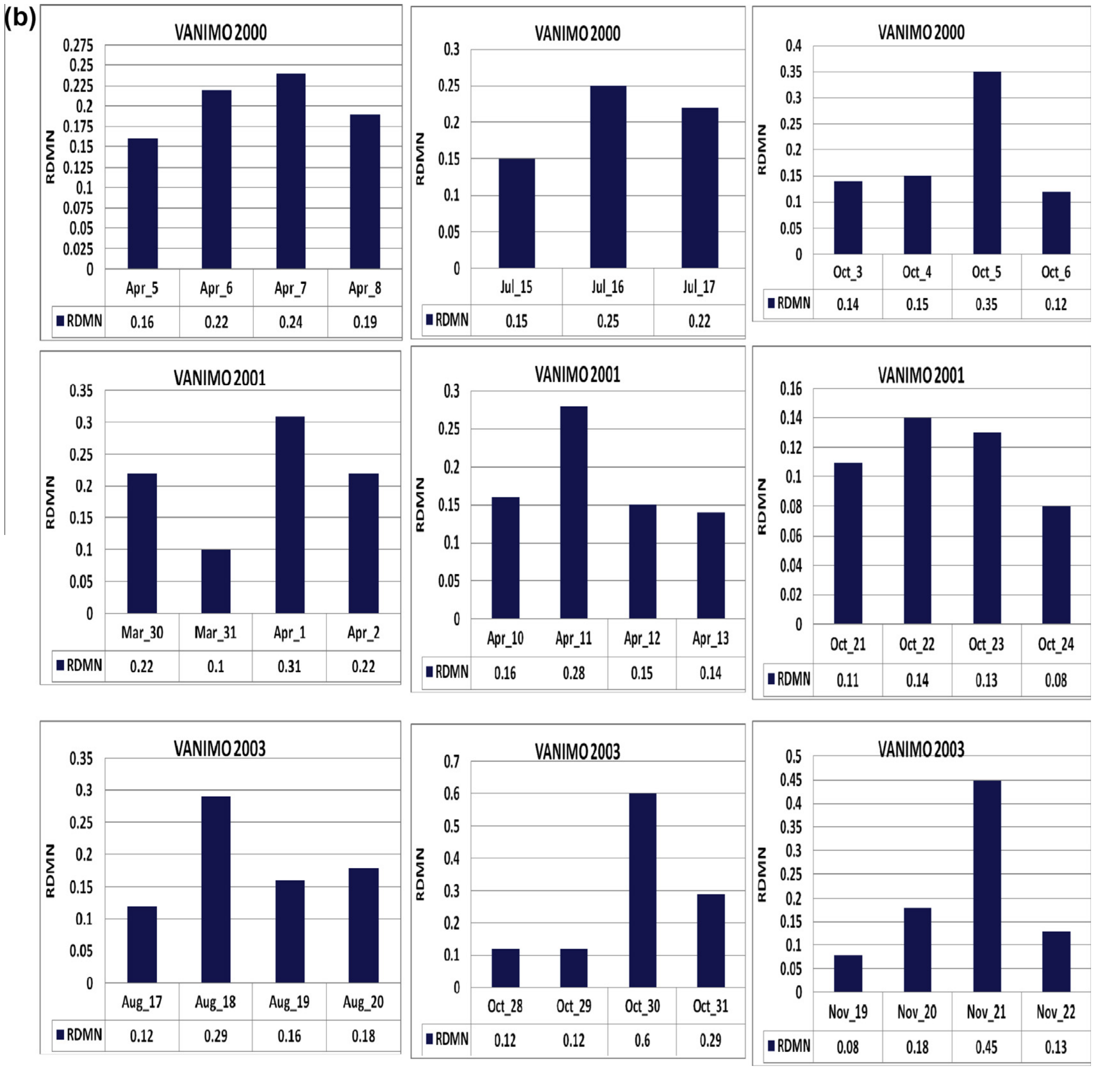

Fig. 10b. Same as Fig. 10a, but for Vanimo station.

be as a result of the fact that electron density at the magnetic equator is higher than at the crest of the equatorial ionization anomaly. As a result the storm model cannot represent these storm time variation patterns since the model was mostly developed with mid-latitude data.

Although, IRI predictions follow the normal trend of diurnal variation of *foF2* measured data, to quantify the performance of IRI-2007, we calculated percentage deviation between the measured storm time *foF2* values and the IRI predictions values for each of the storm periods using Eq. (2). The last panel in each of Figs. 1–9 show the corresponding percentage deviation graph for each storm period. The results obtained generally show that the percentage deviation between the experimental and IRI predicted *foF2* values during main and recovery phases of the storm periods ranges between 40% and 125% (absolute value) at both stations. Exceptions are the storm periods of 3–6 October 2000 (Fig. 3a) at Darwin and 21–24 October 2001 (Fig. 6) at both stations where the relative deviation is less than 40%.

Since mere visual inspection may not be sufficient enough to access the agreement between the experimental values of the IRI predicted values, we therefore employed a criterion called ‘relative deviation module mean’ (RDMM) (Bertoni et al., 2006) to quantify the degree of agreement/disagreement between the experimental values and the predicted values by the IRI model using Eq. (1). The results obtained are as shown in Tables 2a and 2b for Darwin and Vanimo, respectively. According to this criterion, a model exhibits a reasonable to good agreement with the experimental values when the RDMM is less than or equal to 0.06 and a reasonable to poor agreement when RDMM is higher than 0.06.

A closer inspection of Tables 2a and 2b show that, in general, there is reasonable to poor agreement between storm time measured *foF2* values and the IRI storm model prediction values during main and recovery phases of the storms under investigation. This is because RDMM values are generally greater than 0.06. There are a few worse cases where RDMM values are in the range between 0.45 and

0.60 (bold numbers in Tables 2a (October 2000, August, October and November 2003) and 2b (October and November 2003)). A clear picture of the RDMM values can be seen in the bar graphs of Figs. 10a and 10b for Darwin and Vanimo stations respectively. It can be observed that there is a similar trend in the performance of IRI predictions from these two equatorial stations.

4. Discussion and conclusion

We have discussed in this paper the ability of the International Reference Ionosphere IRI-2007 storm time model to predict *foF2* ionospheric parameter from two low latitude stations (Darwin and Vanimo) during nine different geomagnetic storm periods from 2000 to 2003.

As earlier stated, the peak electron density (*NmF2*) of the F2- region of the ionosphere is either increased or decreased during geomagnetic storm periods. These effects can be observed from Figs. 1–9. The observed *foF2* values at Darwin (Fig. 1a) did not show any significant change during the main phase, in comparison to quiet periods, but a positive storm phase (increase in *foF2*) occurred during recovery phase around 18:00 UT (03:00 LT). Positive storm phase occurred during main and recovery phases of the storm period of 17–20 August 2003 (Fig. 7) at both stations during day time on 18 and 20.de Jesus et al. (2012) have discussed extensively response of the ionospheric F-region in the South American and East Asian sectors during an intense geomagnetic storm of August 2005. It was reported that *foF2* variations show a positive storm phase on the night of 24–25 August at Palmas (PAL; 10.2° S, 48.2° W; dip latitude 6.6° S) and Sao José dos Campos (SJC; 23.2° S, 45.9° W; dip latitude 17.6° S), Brazil, during the recovery phase. They suggested that the positive storm phase may be a result of prompt penetration of electric field of magnetospheric origin that result in abrupt increase in *foF2* at PAL, SJC at about 12:00 UT.

Similar result was also reported by de Abreu et al. (2011) at equatorial and low latitude regions in the Brazilian sector during the super geomagnetic storm on 15–16 May 2005. Their investigation showed that during the daytime on 15 and 16 May, in the recovery phase, the variations in *foF2* at Sao José dos Campos SJC (23.2° S, 45.9° W; dip latitude 17.6° S), and the vTEC observations, particularly at Brasília (BRAZ; 15.9° S, 47.9° W; dip latitude 11.3° S), P. Prudente (UEPP; 22.1° S, 51.4° W; dip latitude 14.4° S), and Porto Alegre (POAL; 30.1° S, 51.1° W; dip latitude 20.5° S), show large positive ionospheric storm.

A strong negative storm phase (decrease in *foF2*) was observed at both stations for storm period of 3–6 October 2000 on 5 October during recovery phase (Fig. 3). Similar negative storm phase in *foF2* was observed at both stations on 30 October for the storm period of 28–31 October 2003 (Fig. 8) and on 21 November for storm period of 19–22 November 2003 (Fig. 9). The negative storm phase may be as a result of neutral composition changes (Prölss and Werner, 2002).

Similar large negative phase in *foF2* at the equatorial station Fortaleza (3.9° S, 38.4° W) and at the ionization anomaly crest station Cachoeira Paulista (22.5° S, 45° W), in the Brazilian sector, during the great geomagnetic storm of 13–14 March 1989 has also been reported by Batista et al. (1991).

A detailed analysis of response of equatorial ionosphere during a large number of severe magnetic storms has been carried out by Lakshmi et al. (1997). They also observed, on a large number of occasions, that in the post-midnight periods the *foF2* values collapse to levels significantly lower than their monthly median values during severe storms. This collapse in *foF2* during magnetic storms could be due to changes in the magnitude as well as in the direction of usual equatorial electric field.

Previous results have shown that the IRI storm model does not predict well at the equatorial region since its development was mostly based on *foF2* data from mid-latitude ionospheric stations (Araujo-Pradere and Fuller-Rowell, 2003; Oyeyemi and Adewale, 2009). The results we obtained show that the outputs of the model reasonably follow the normal variation of the experimental values but do not reproduce well the measured values. Evidence of this can be seen from the results of the ‘relative deviation module mean’ (RDMM) obtained during all the storm periods under investigation. The results show that there is reasonable to poor agreement between the model prediction values and the measured *foF2* storm time values. This is because RDMM values are greater than 0.06 during the main phases and early stage of recovery phases of all the storm periods under investigation from the two stations.

Analysis of the percentage deviation of the measured values with respect to the IRI model values is in the range of 40–125%. A reasonable to good agreement is observed at Darwin during the main phase of the storm period of 5–8 April 2000 (Fig. 1a) during main phase. In general, IRI model mostly overestimate data during the storm periods for Darwin station and underestimate *foF2* data for Vanimo station. These differences could be related to higher solar activities in 2000 ($Rz = 119$) and 2001 ($Rz = 111$). It is well established that increase of the eastward electric field is usually observed during severe geomagnetic storms (Blanc and Richmond, 1980; Scherliess and Fejer, 1997). This increase usually due to ionospheric dynamo leads to large upward plasma drift at the equatorial latitudes which brings about decrease in the electron density (*NmF2*) (Blanc and Richmond, 1980; Scherliess and Fejer, 1997; Basu et al., 2001). The electric field effects are not currently accounted for in the development of the IRI storm model and as such predictions by IRI model are usually greater than the experimental values at the equatorial region. In the same way, enhancements of *NmF2* (i.e. positive ionospheric storms) can also occur at the equatorial sector of the ionosphere during geomagnetic storms. This enhancement is attributed to decrease in the eastward electric field (Fejer, 1981, 1991). Effects of these phenomena have been observed in the increase and decrease of *foF2* values during storm periods under investigation in this study.

It is evident from this study that further studies at the equatorial region including other sectors of the ionospheres (in addition to those studies already carried out) are required to establish a possible ionospheric dynamo dependence of the accuracy in *foF2* predictions. These studies will help at improving the performance of IRI model both at the equatorial region of the ionosphere as well as on a global scale.

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