



## Storm time IRI-Plas model forecast for an African equatorial station

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### ABSTRACT

The limitation of ionospheric models in describing short-term ionospheric events has led to the development of data assimilative models e.g. the International Reference Ionosphere extended to Plasmasphere (IRI-Plas) model. This paper compares the IRI-Plas derived total electron content (TEC), the peak height (hmF2) and critical frequency (foF2) of the F2-layer with those obtained from Global Positioning System (GPS) receiver's and Digisonde Precision Sounder (DPS-4) measurements over Ilorin (Geog. Lat. 8.50°N; Long. 4.50°E, dip: − 7.9°) during geomagnetic storm days. The model estimation was done by assimilation of Ionosonde foF2 and TEC derived from GPS (GPS-TEC) and Global Ionospheric Map (GIM-TEC) into the model code. In order to study the effect of data assimilation on the model's representation, the “no input” option of the model was used as reference. The result shows that with the exception of the foF2 assimilation mode, all the options generally reproduced TEC quite well for all the storm days considered. Overall, the model adjusted with GPS-TEC gives the best prediction of TEC as it reduced the prediction error of TEC by a multiple of up to three compared to using the GIM-TEC. Also, all the options failed to reproduce the storm induced prominent features in the storm-time features of foF2 and hmF2. In other word, assimilation with the TEC does not generally improve the storm-time predictions of foF2 and hmF2 at the station. Consequently, for storm-time estimation of the F2-layer peak parameters, the ‘no input’ representation of the model is more valid at this station.

### 1. Introduction

A reliable assessment of the space weather impact on the geospace is important for efficient operations of satellite-based communication and navigation technologies. The estimations, which are required during the planning stage of these technologies, are done using ionospheric climatological models such as the International Reference Ionosphere (IRI) model. The IRI model is developed jointly by Committee on Space Research and the International Union of Radio Science and has been recognized by the International Standard Organization (ISO) to specify the Earth ionospheric plasma parameters Bilitza et al. (2017). The model is continuously updated as new and reliable measurements become available or new modeling techniques are discovered which gives rise to the different versions of the model. Studies to validate the IRI model at different regions have been conducted by different authors e.g. Adebisi et al., 2014; Adebisin et al., 2014; Adebisi et al., 2016a, b; Grynszyna-Poliuga et al., 2015; Scidá et al., 2012; Olawepo et al., 2017 etc.

Results from some of these studies have revealed discrepancies in the performance of the model, some of which have been attributed to its inability to account for the plasmaspheric contribution to the ionospheric total electron content (TEC) e.g. Scidá et al., 2012. Consequently, several plasmasphere models have been proposed to extend the IRI model to plasmaspheric altitudes. The framework of the proposed model is aimed to specify the ionospheric parameters of interest up to the plasmaspheric height at any interest location for different solar and geomagnetic conditions. Among these candidate models is the IZMIRAN plasmasphere model (IRI-IZMIRAN) (henceforth referred to IRI-Plas model): an empirical model that is based on whistler and satellite observations (Chasovitin et al., 1998; Gulyaeva et al., 2002). Up to the peak height of the F2-layer, the bottomside profiles of the IRI and IRI-Plas models are the same because both models employed the CCIR or URSI map to model this section of the ionosphere (Gulyaeva et al., 2011). However, the topside profile of the IRI-Plas model is improved using the topside sounder data from International Satellite for Ionospheric Studies (ISIS) 1,

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ISIS 2 and Russian Intercosmos – 19 satellite (IK-19). For the plasmaspheric extension of the model, the topside density profile and the plasmaspheric density profile provided by the Russian Standard Model for the ionosphere (SMI) plasmasphere model are linked at an altitude of one basic scale height above the F2 layer peak height (Chasovitin et al., 1998). The basic scale height is the height above the F2 layer peak height where the maximum electron density (NmF2) decays to  $NmF2 \cdot 1/e$ , where  $e$  is the Euler number ( $\sim 2.718$ ).

In addition to the plasmaspheric extension of IRI-Plas model, the model algorithm can be adjusted with external data which help to capture the presence of any short-term dynamics in the ionosphere and plasmasphere due to some transient disturbances (e.g. disturbance due to geomagnetic storm event etc.). Assimilation of the model with external TEC data allows update of the scale height thus providing instantaneous value of the three key parameters (TEC, foF2 and hmF2). In the assimilative mode of operation of the model, the instantaneous values of the three parameters is determined from the reference quiet time monthly median value of each parameter. The reference quiet time value of the F2-layer critical frequency (or peak density) or peak height (i.e. qfF2 and hqF2) can be estimated either from the CCIR model or data. The pre-fit TEC (TECq) is calculated from the first iteration of the model algorithm by integrating the profile produced by CCIR estimated qfF2 and hqF2. The value of foF2 (i.e. instantaneous or reconstructed critical frequency) is estimated from the model adapted-TEC using Eq. (1):

$$f_oF_2 = f_qF_2 \left( \frac{TEC_{input}}{TEC_q} \right)^{\frac{1}{2}} \quad (1)$$

Where  $TEC_{input}$  is the external TEC that is assimilated into the model. The instantaneous value of hmF2, associated with changes in the critical frequency, is deduced from the empirical model described in Gulyaeva (2012) while the re-constructed electron profile due the instantaneous values of foF2 and hmF2 produces the post-fit TEC (Gulyaeva et al., 2011).

The performance of this model at different region has been reported in various studies (e.g. Bolaji et al., 2017; Adebisi et al., 2016a, b, 2017; Gulyaeva, 2011; Maltseva et al., 2013; Zakharenkova et al., 2015; Gordiyenko et al., 2018; Okoh et al., 2018; Ezquer et al., 2017). Adebisi et al. (2016a, b), Bolaji et al. (2017) and Okoh et al. (2018) compared the performance of IRI-Plas with other ionospheric models such as the IRI and NeQuick-2 models in the African region. In Adebisi et al. (2016a, b), the predictions of the IRI-Plas and the three topside options of the IRI models were found to show latitudinal and seasonal trends. In other words, IRI-Plas model was found to perform better than the IRI in months and seasons where the IRI model underestimates TEC. The result was however attributed to the absence of the plasmaspheric electron content in the GPS-TEC. In a similar investigation by Ezquer et al. (2017) at some low latitude stations in South American sector, the discrepancies between the modeled and measured TEC for both IRI-Plas and NeQuick-2 were also found to show latitude and seasonal variations. Also, studies like Gordiyenko et al. (2018) and Maltseva et al. (2015) compare TEC and the electron density profile estimated by IRI-Plas model with their corresponding observed value at the Asian and European sector respectively. Gordiyenko et al. (2018) found a daytime overestimation of electron profile in all the seasons between the altitude of 400–2000 km and between the altitude of 600–1600 km near the mid-night hours. Maltseva et al. (2015) on the other hand employed the TEC adaption mode of operation of the model to investigate the storm time behavior of the over a station located in the European sector. They suggested that the model can compensate with much higher accuracy the ionospheric induced error.

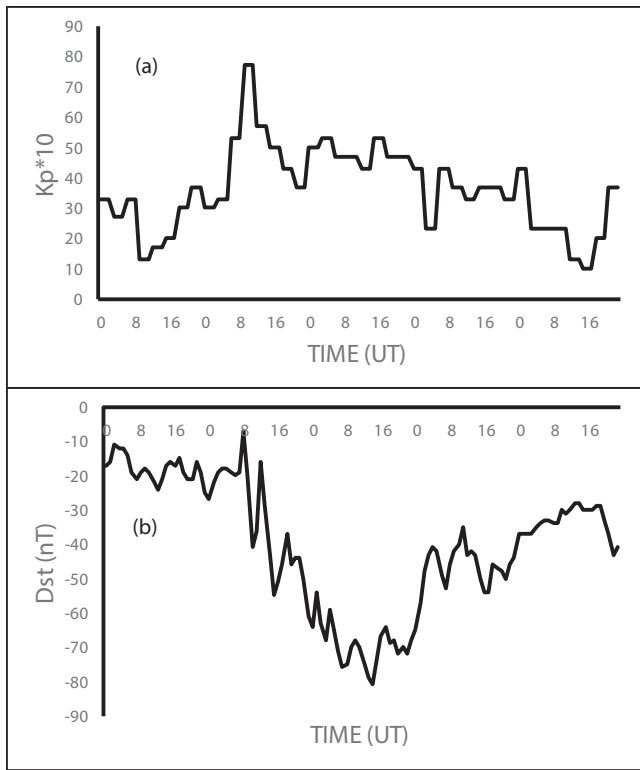
The rapid maps of foF2 and hmF2 are on high demand in space-based communication and positioning systems. Such maps are scarce in the region of Africa due to the paucity of ionosonde data. One way to overcome this challenge is by modifying the IRI-Plas code with external measured TEC. By adjusting the model with experimental data, the

ionospheric dynamics and morphology represented by the data could be revealed by the model, while still maintaining its overall integrity. The adjusted model may give a more realistic representation of foF2 and hmF2 values. Adebisi et al. (2017), had earlier evaluated the performance of using GIM-TEC in the IRI-Plas model assimilation for the estimation of TEC, foF2 and hmF2 at equatorial stations for both quiet and disturbed geomagnetic conditions. Though, a significant improvement was observed (by the Authors in Adebisi et al., 2017) in the modeled TEC for most of the months and seasons, the result of foF2 and hmF2 are however generally poor at the locations. Consequently, certain questions may come to fore. They are: (i) what are the effects of the error due to spatial interpolation in GIM-TEC's cell calculation on the results obtained by Adebisi et al. (2017)? (ii) How is the IRI-Plas-TEC and IRI-Plas-hmF2 affected when the model is assimilated with foF2 alone, and (iii) when used with TEC? This forms the focus of this work. The aim is to get the combination of the model options that give more reliable estimate out of the three key ionospheric parameters (TEC, foF2 and hmF2). Consequently, the efficacy of using the GIM-TEC for model assimilation in predicting the three parameters is evaluated. This is achieved by comparing the result of the predictions of GPS-TEC assimilation option with that of GIM-TEC.

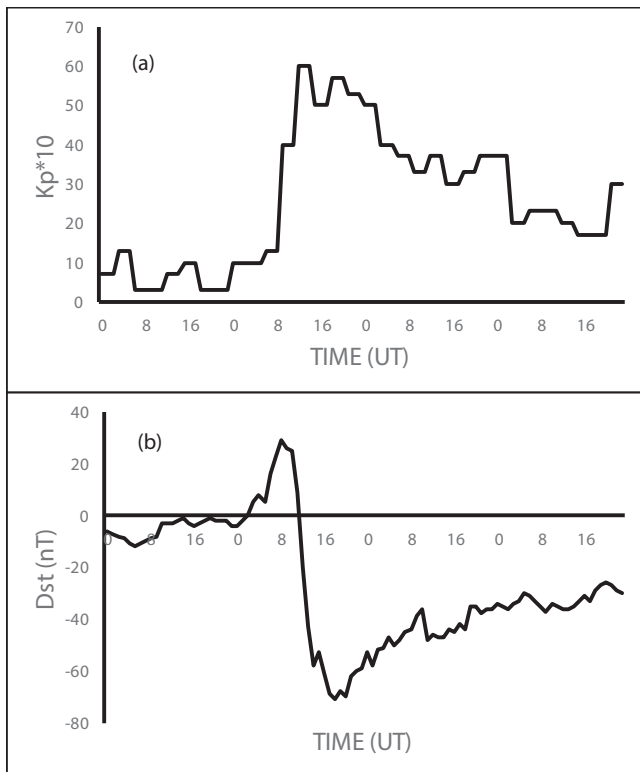
## 2. Materials and methods

In this paper, we compared the measured TEC, foF2 and hmF2 data with the corresponding IRI-Plas modeled values during some disturbed days in the year 2010. The GPS data and the F2 layer peak parameters (foF2 and hmF2) used for the investigation were obtained from the measurements of the GPS receiver and the Digisonde Portable Sounder (DPS) respectively. Both instruments are located at the University of Ilorin ionospheric observatory, Ilorin (Geog. Lat. 8.50° N, Long. 4.50° E, dip -7.9°), an equatorial station in West Africa. The GPS receiver at Ilorin is part of a network of Scintillation Network Decision Aid (SCINDA); which is a network of ground based receivers that monitors scintillations at the UHF and L band frequencies caused by electron density irregularities in the equatorial ionosphere (Olawepo et al., 2015). The DPS at Ilorin was installed in March 2010 and it acquired data continuously up till January 2011. In this paper, only storm events in which there are simultaneous GPS and DPS data were considered. Consequently, we have selected the moderate geomagnetic storm events which occurred on 5 April, 2 May, 29 May and 4 August 2010 for this present investigation. Figs. 1, 2, and 3 show the time variations of Disturbance storm time (Dst) and the planetary K (Kp) indices of each of these storm events. The TEC analysis software developed by Gopi Krishna Seemala was used to retrieve TEC from the raw GPS measurements. Readers are referred to Ndeda and Odera (2014) and Rama-Rao et al. (2006) for detailed on the TEC retrieval analysis.

The modeled parameters are estimated using the latest version of the model - IRI-Plas 2017 model. The major change in this recent version of the model compared to the old version is the replacement of the global effective ionospheric (IG12) index (which is based on ionosonde measurements) with the solar and ionospheric Global Electron Content (smoothed by the sliding 12-months window) (GEC12) indices (Gulyaeva, 2016; Gulyaeva et al., 2017). Readers can also visit <http://ftp.izmiran.ru/pub/izmiran/SPIM/readme.txt> for detail of the new changes made in the model from the year 2010. In this investigation, the calculation of the modeled values is done using the online space weather services of the IONOLAB group and is available at [www.ionolab.org](http://www.ionolab.org). The online service makes use of the IRI-Plas software provided by the IZMIRAN Institute. The model-derived parameter can be done in two modes. The default option of the model which is referred to as the “no input” option and the data assimilative option. The “no input” option of the model gives a set of parameters that is estimated when the model has not been adjusted with external data. The data assimilative mode allows the ingestion of the ionosonde measurements (foF2 and hmF2) and TEC into its code. This will enable the model to capture the dynamics present

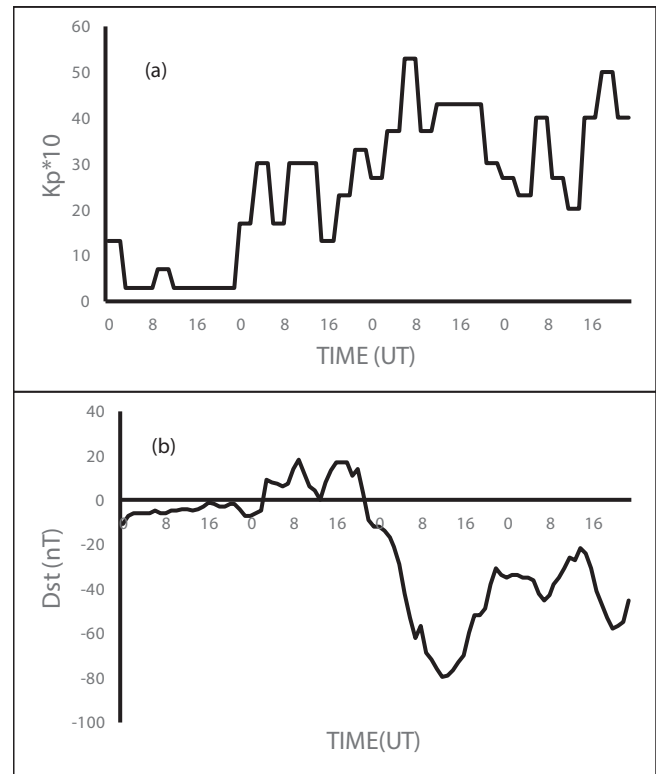


**Fig. 1.** The time variation of (a) Kp and (b) Dst indices for the period 4–8 April, 2010.



**Fig. 2.** The time variation of (a) Kp and (b) Dst indices for the period 1–4 May, 2010.

in the ionosphere. In this investigation, the model has been adjusted using the (i) GPS derived TEC (GPS-TEC) (ii) TEC derived from Global



**Fig. 3.** The time variation of (a) Kp and (b) Dst indices for the period 27–30 May, 2010.

Ionospheric Map (GIM-TEC) and (iii) ionosonde foF2. For the model estimation of TEC and hmF2, all the three input (i) – (iii) are employed while only options (i) and (ii) are used in the prediction of foF2. The value of GIM-TEC available on the IONOLAB interface, that is input automatically for each hour, is used in our investigation. The Root Mean Square Error (RMSE) i.e. the prediction error (denoted by  $\sigma$ ) of each of the model options is calculated using Eq. (2).

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (\beta_{OBS} - \beta_{MOD})^2} \quad (2)$$

Where  $\beta_{OBS}$  and  $\beta_{MOD}$  are the observed and modeled values of the three parameters respectively and  $N$  is the number of data points.

To evaluate the effect of assimilation on the model performance, we have used the model prediction when operated with no external data input as a standard of comparison for the assimilative options. The deviation,  $\rho$  (in percentage), between the “no input option” and any assimilative option is calculated using Eq. (3).

$$\rho = \frac{\sigma_o - \sigma_i}{\sigma_o} \times 100 \quad (3)$$

Where  $\sigma_o$  and  $\sigma_i$  are the prediction errors when the model is operated with “no input” and with data input modes respectively.

Since the GPS receiver at Ilorin is not part of the International GNSS Service (IGS) network of receivers used in the production of the GIM, we have estimated a factor, denoted by  $\alpha$ , to compare the values of  $\rho$  for both GPS-TEC and GIM-TEC assimilations options of the model's prediction of TEC. This is to enable us determine the efficacy of using the GIM-TEC for model assimilation in region like Africa where GPS receivers are far apart. The constant  $\alpha$  is defined in Eq. (4) as:

$$\alpha = \frac{\rho_{GPS-TEC}}{\rho_{GIM-TEC}} \quad (4)$$

Where  $\rho_{GPS-TEC}$  and  $\rho_{GIM-TEC}$  are the values of the percentage deviation for GPS-TEC and GIM-TEC assimilation for TEC prediction.

### 3. Results

#### 3.1. Response to the geomagnetic storms

Fig. 4 (a) to 4 (l) shows the effects of the four moderate geomagnetic storm events on TEC, foF2 and hmF2 at Ilorin. It is observed generally that while TEC and foF2 experienced more of enhancement, hmF2 show more negative effect. Readers are hereby referred to Joshua et al. (2018) for detailed description of the effects of the events on the ionosphere over Ilorin. The focus of this paper is to evaluate the capability of the IRI-Plas model in predicting the three key ionospheric parameters when adjusted with various input parameters during these storm events.

#### 3.2. Model validation

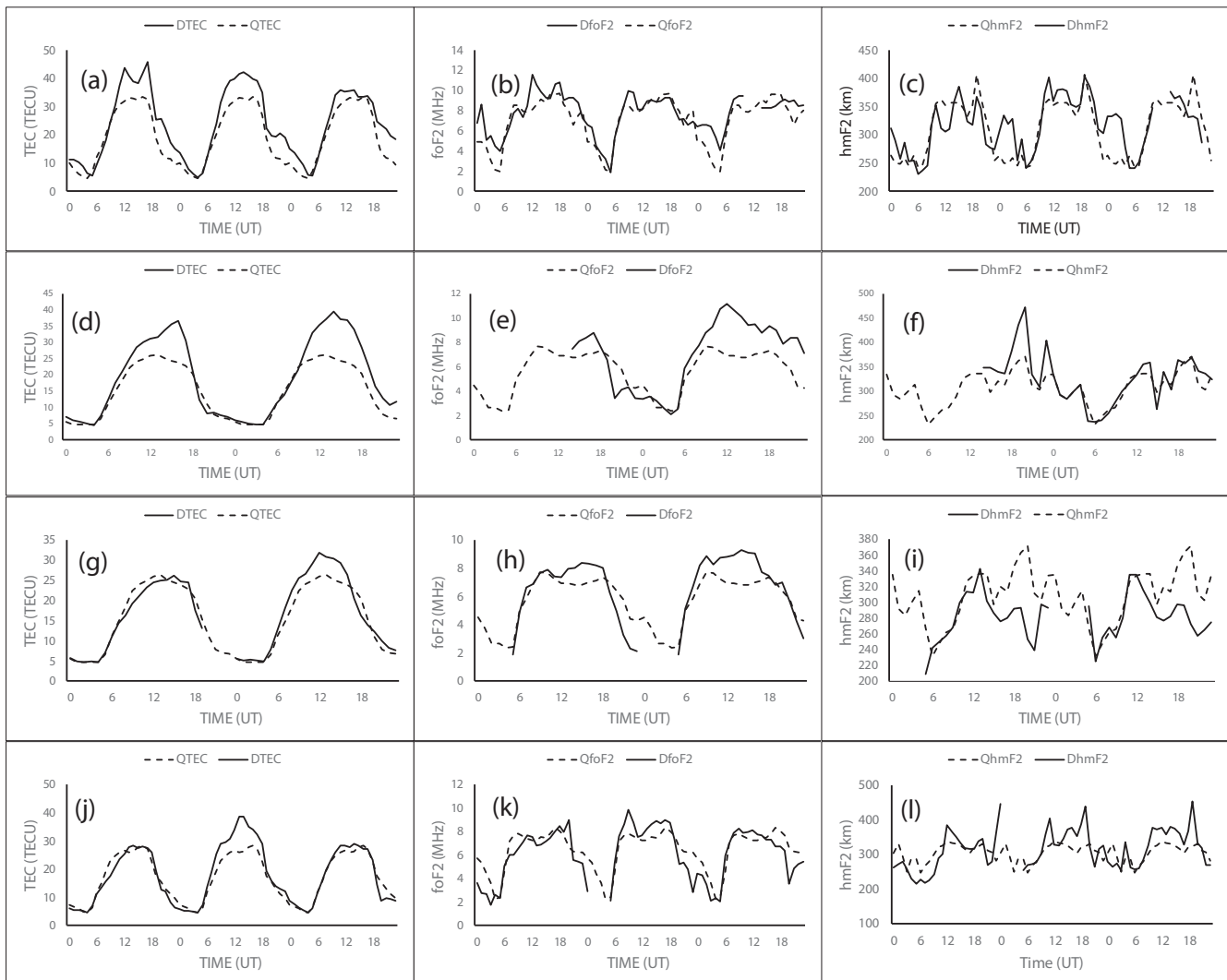
##### 3.2.1. April 5, 2010 geomagnetic storm

Fig. 5 (a) – (c) shows comparisons of values of the three parameters under study obtained through experiment and different options of IRI-Plas model i.e. IRI-Plas with no external input, IRI-Plas with GIM input and IRI-Plas with experimental foF2 and GPS-TEC data during the

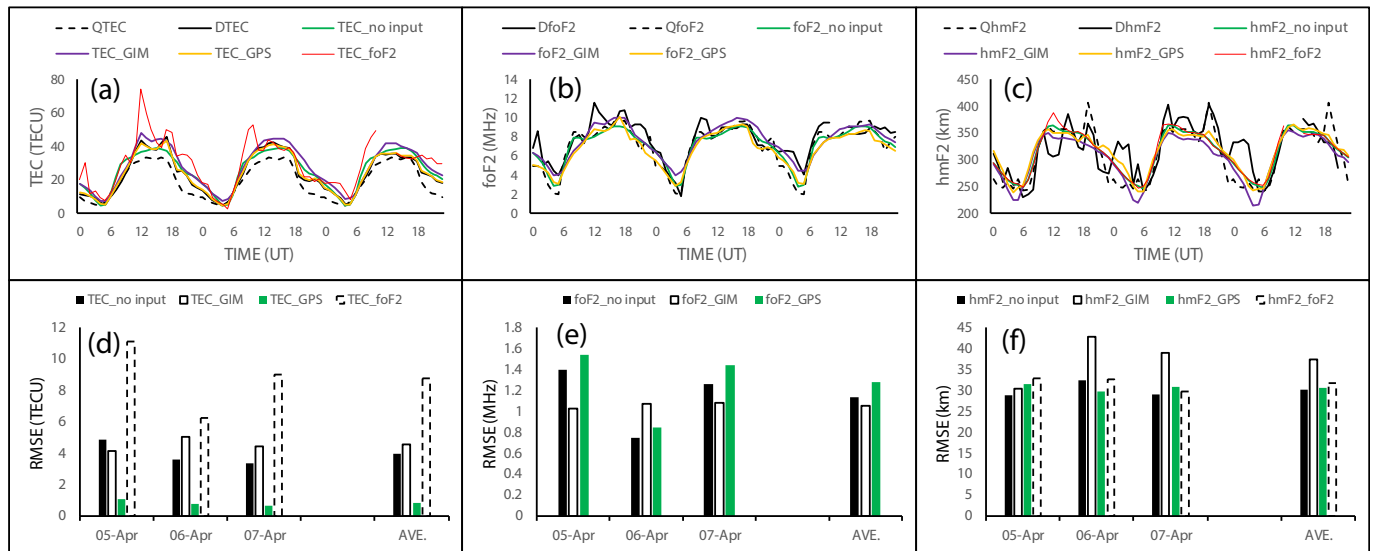
disturbed days of 5–7 April 2010. In Fig. 5 (a), it is generally observed that all the options of the model give good representation of the enhancement in the GPS-TEC during the storm days. Specifically, all the options of the model except the ‘no-input’ option give a good representation of the double-peak structure found in the variation of the observed TEC on 4 April. It is however observed that the foF2 adjusted model gives unusually large amplitudes of the double - peak structure of TEC in the first day of storm.

Fig. 5 (b) and (c) show the values of the modeled of foF2 and hmF2 in comparison with the observed values during the disturbed days. The plots also include the reference average quiet time variation. Although all the options give a close representation of IRI-Plas-foF2 trend, there are however, episodes of overestimations and underestimations in its representation. No options of the model, particularly the “no input option”, reproduced the observed structure of the disturbed foF2. For example, the double peak structure and the nighttime enhancement recorded on the 5 April and the enhancement in the pre-noon peak on 6 April were overestimated. We also observed major disagreements between the observed and modeled hmF2 by all the options. In other words, none of the model options has the capability to reproduce the storm-induced changes in F2-layer height observed during the storm days.

The bar charts in Fig. 5 (d) – (f) show the graphical representations of the prediction error for all the model options. The results indicate that there is a significant reduction in the prediction error ( $\rho_{GPS-TEC} = 80\%$ )



**Fig. 4.** The storm-time variation of TEC, foF2 and hmF2 in comparison with their average quiet-time variation at Ilorin during the geomagnetic storm days of (i) 5 April 2010 (a–c) (ii) 2 May 2010 (d–f) (iii) 29 May 2010 (g–i) and (iv) 4 August 2010 (j–l).



**Fig. 5.** (a–c) shows the variation of the IRI-Plas modeled parameters as well as the average quiet and storm time variations at the station during the storm days of the 5 April 2010 geomagnetic storm event (d–f) shows the prediction errors of all the model options together with their respective average values for all the storm days considered.

when the model is adjusted with GPS-TEC. On the other hand, the result of the assimilations of GIM-TEC and foF2 did not show any improvements in the prediction of IRI-Plas-TEC, this is more so for the foF2 assimilation option. TEC is overestimated and its storm-induced features are not well represented when the model is adjusted with GIM-TEC and foF2, hence the high value of their prediction errors relative to the no input option as seen in Fig. 5 (d). Also, there is no significant difference in the values of the prediction error of foF2 and hmF2 for all the model options. This result may suggest that the no input option representation of foF2 and hmF2 is still valid at the station.

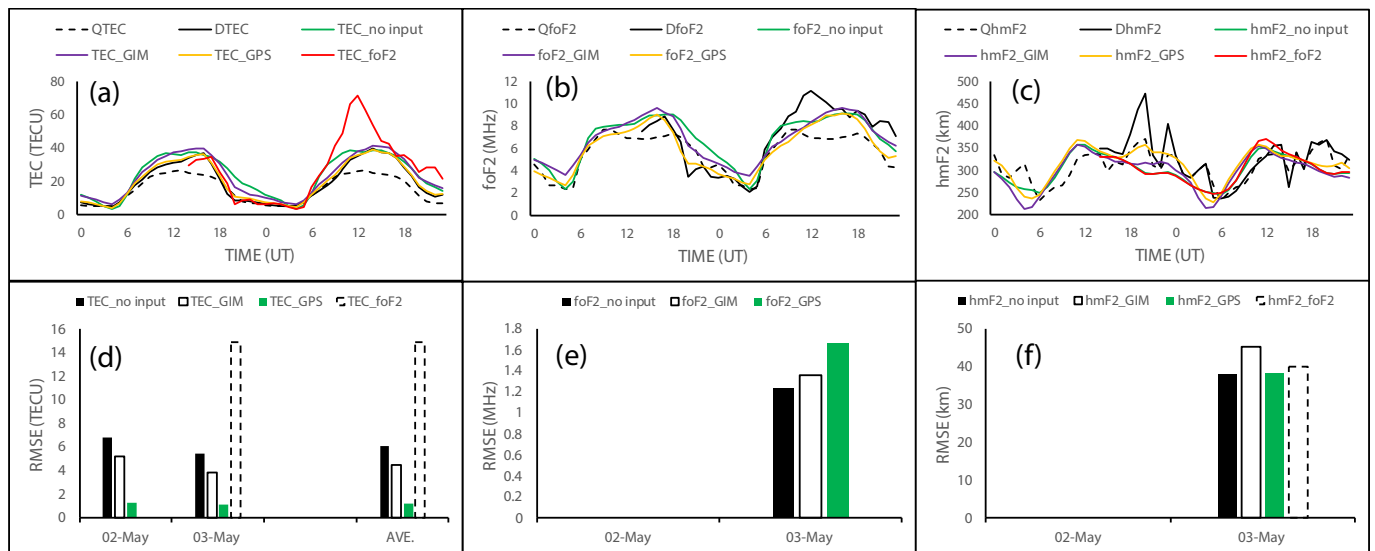
### 3.2.2. May 2, 2010 geomagnetic storm

Fig. 6 (a) – 6 (c) shows the performance of different options of IRI-Plas model at representing the storm time features of the three parameters (i.e. TEC, foF2 and hmF2) during the storm days of 2–3 May, 2010. Again, all the options reproduced TEC quite well on those two storm days except for the foF2 assimilation option, which overestimated the

enhancement much significantly. Although, both the GPS-TEC and GIM-TEC assimilations give good representations of TEC, overall, the GPS-TEC assimilation gave the best representation of IRI-Plas-TEC.

Fig. 6 (d) – (f) shows the chart of the prediction errors for all the parameters for the two storm's days. The plots also include the average values of the prediction errors for all the parameters for the two days. As shown in the bar chart, using GPS-TEC and GIM-TEC in the model's assimilation reduced the prediction errors very significantly. The percentage deviation in TEC prediction errors for both  $\rho_{GPS-TEC}$  and  $\rho_{GIM-TEC}$  are 81% and 27% respectively. These values translate to  $\alpha = 3$ , which means that adjusting the model with GPS-TEC improves the modeled TEC 3 times better than using the GIM-TEC.

Again, all the model options failed to reproduce the prominent storm induced features in both the foF2 and hmF2. For example, the enhancement in the foF2 on 3 May and the sharp increase in F2 layer peak height on 2 May were both absent in the modeled foF2 and hmF2 respectively for all the model options as shown in Fig. 6 (b) and (c). The



**Fig. 6.** (a–c) shows the variation of the IRI-Plas modeled parameters as well as the average quiet and storm time variations at the station during the storm days of the 2 May 2010 geomagnetic storm event (d–f) shows the prediction errors of all the model options together with their respective average values for all the storm days considered.



values of the prediction errors in both foF2 and hmF2 also indicate that none of the assimilation options performed as good as the no input option at representing their storm time features. In other words, the model performed better on its own in predicting hmF2 and foF2 without any external input.

### 3.2.3. May 29, 2010 geomagnetic storm

Fig. 7 (a) – (c) shows the performance of the various options of IRI-Plas model at predicting the parameters during the storm days of 28 and 29 May geomagnetic storm event. The plots also include the quiet and storm time variation of the three parameters. It can be observed that both the GPS-TEC and GIM-TEC assimilation options reproduced TEC quite well on the 28 May. However, the no input and foF2 assimilation options overestimated the TEC value very significantly. Again, the GPS-TEC assimilation option gives the best prediction of the modeled TEC (with average RMSE of 1.39 TECU) and the worst is the foF2 assimilation (with average RMSE of 7.92 TECU) as indicated in the bar chart in Fig. 7 (d). Comparing the deviation due to the GPS-TEC and GIM-TEC assimilation, it was observed that the deviation with GPS-TEC input (i.e.  $\rho_{GPS-TEC}$ ) is higher (with an average value of  $\sim 79\%$ ) than  $\rho_{GIM-TEC}$  (with a value  $\sim 67\%$ ). These values also translate to  $\alpha = 1.2$ .

From Fig. 7 (d) – (f), it can be observed that all the options underestimated foF2 value during the storm period; however, the no input option gave a better prediction of the structure than both the GPS-TEC and GIM-TEC assimilation options particularly during the night period. Again all the options could not predict the decrease in the F2 layer height found in the observed value for the two storm days. On the average, the no input option gives a better prediction of hmF2 and foF2 than the other options.

### 3.2.4. August 4, 2010 geomagnetic storm

Fig. 8 (a) – (c) shows the model representations of the three parameters together with their average quiet time and storm time variations during the storm days of 3–5 August 2010. Again, the enhancement observed in the storm-time TEC values is well reproduced by both the GPS- and GIM-TEC input options. The model representations with foF2 input and “no input” however overestimated and underestimated the value of TEC respectively. All the options give close representation of foF2 but failed to predict the prominent features observed in the storm time structure such as the enhancement in the pre-noon peak recorded on the 4 August. Similar observation is recorded in the model representation of the storm time structure of hmF2. Again, all the options could not predict the increase in the F2-layer peak height that was observed on the 4 and 5 August.

Fig. 8 (d) – (f) is chart showing the prediction error of all the model options for the three parameters. Again, the prediction errors of the modeled TEC is found to be reduced much significantly when the model is operated with GPS- and GIM-TEC input. However, the value of the foF2 assimilation is high compare to the no input option. In general, the model with GPS-TEC input has lowest prediction error for the modeled TEC while the model with foF2 input has the highest. The average of percentage deviation for IRI-Plas-TEC with GPS-TEC and GIM-TEC input are 76% and 49% respectively. This translates to  $\alpha = \sim 1.6$ , which also indicate a very good performance of the model with GPS-TEC input than with GIM-TEC input.

Overall, for the model prediction of hmF2 and foF2, no significant difference between the prediction errors when the no input option of the model is implemented and when there is ingestion of external data. This also suggest that the no input of the model is effective for the storm time estimation of the of the F2-layer peak parameters.

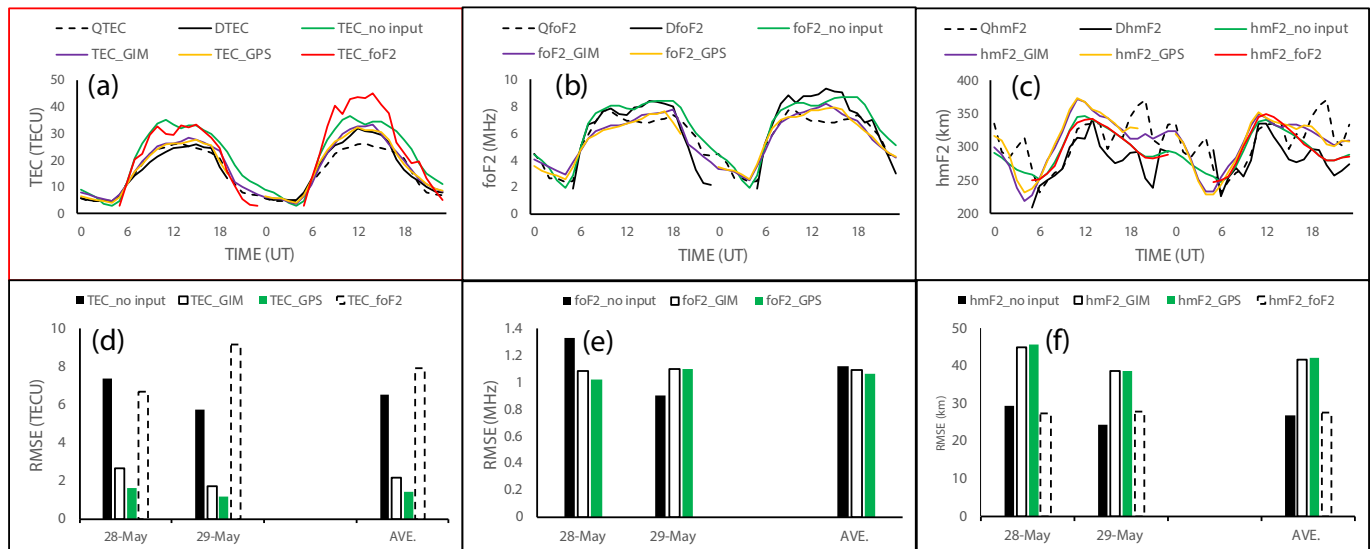
## 4. Discussion

We have evaluated the performance of the various options of the IRI-Plas model in an equatorial station in Africa. Generally, we found that the model performed better in reproducing TEC particularly when the model

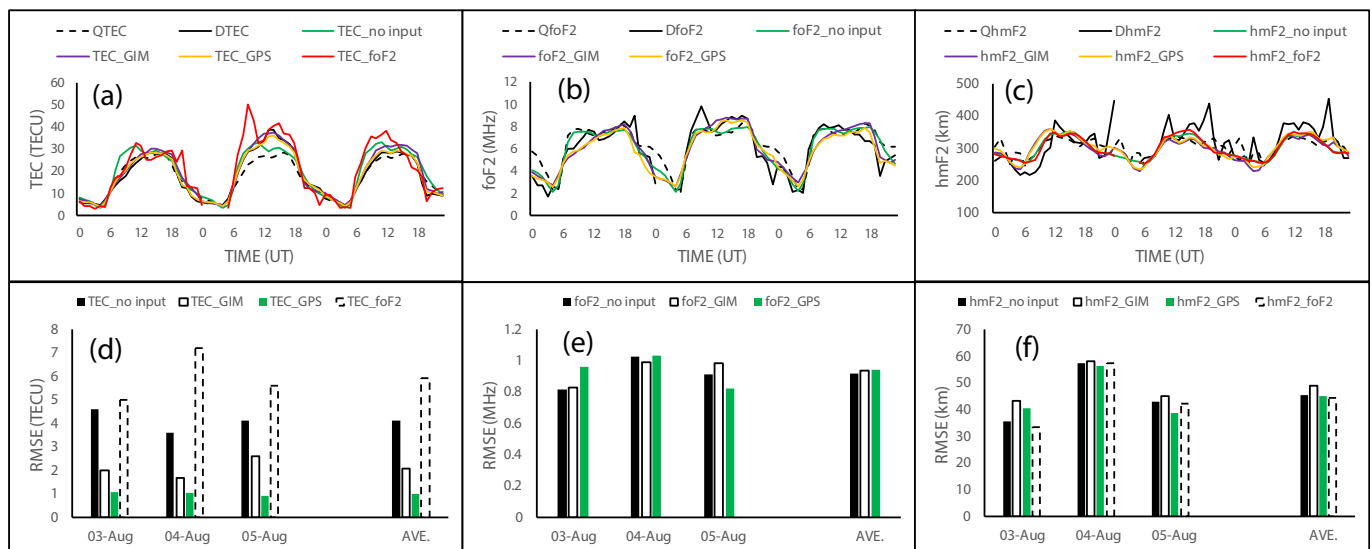
is adjusted with GPS-TEC. The IRI-Plas modeling framework allows ingestion of the measured value of TEC. Thus, the state of the ionosphere that is captured in the measured value is reflected in the model representation and this may explain why both the GPS-TEC and GIM-TEC assimilation options give better representations of TEC during the storm events. On the other hand, we found that the GPS-TEC assimilation option gives a better prediction of TEC than using the GIM-TEC for the model assimilation. One major source of data-model offset in GIM-TEC assimilative mode is error due to spatial interpolation in the calculation of TEC in the GIM cell. The GIM is produced by the ionosphere working group of the IGS using raw RINEX data from the network of International GNSS Service (IGS) receivers. Readers are referred to Hernández-Pajares et al. (2009) for more details on IGS TEC map. The spatial distribution of the IGS receivers in Africa is of several thousands of kilometer from one to another, particularly in the Western region where Ilorin is located. The complex spatial interpolation process between two stations of several kilometers apart may yield TEC values that may be far from the observed values due to computational error in the interpolation routine. This may have contributed to the significant difference observed between the model predictions with GPS-TEC and GIM-TEC inputs.

Furthermore, the result of foF2 assimilation shows that the model failed to give a good representation of the magnitude and morphology of TEC and hmF2 in all the storm days considered. Overestimation of TEC is generally observed with foF2 input. Similarly, the modeled peak parameters derived with TEC input (either with GPS-TEC or GIM-TEC) are also found to differ from the measured values. These data-model disagreements can be attributed to the model shortcomings in the region. For example, adapting the model with foF2 alone allows the bottom side portion of the electron density profile to be re-scaled. The result obtained when the model is adjusted with foF2 may indicate that the challenge may not be the re-scaling process but may be a challenge with the formulations describing bottomside portion of the density profile which cannot be corrected by re-scaling. This may be because this portion of the model is not well modeled to capture the storm induced dynamics in the region. For a well modeled profile, the functions or coefficients describing the portion must reflect the characteristics of the ionosphere at in the region of interest. Since the bottomside portion is modeled using ionosonde data different from the Africa region, the spatial paucity of ionosonde in the region (hence the non-inclusion of measurement from the region) may limit the performance of the model in the region very significantly. Likewise, the topside portion of the density profile is re-scaled when the model is adjusted with TEC. In the IRI-Plas code, the decomposition of the TEC (either GPS-TEC or GIM-TEC) during the assimilation process results into the reconstruction of the F2-layer peak electron density (which is proportional to the F2-layer critical frequency) and topside scale height ( $H_{sc}$ ) (Gulyaeva et al., 2011). Reconstruction of the instantaneous foF2 requires the model driven quiet-time reference value (fqF2). This quiet time reference value is derived from CCIR predictions (Gulyaeva et al., 2011). Since CCIR model for foF2 is an observational based model derived from networks of ionosonde measurements, this may contribute to the poor performance of the model.

Other shortcoming of the model that may contribute to the TEC data-model discrepancy includes the inaccurate estimation of the actual contribution of the plasmasphere to TEC. For example, the plasmaspheric contribution to GPS-TEC may be significant particularly during geomagnetic storm. The IRI-Plas derived TEC is a combination of both the ionospheric and plasmaspheric TEC and may differs the observed TEC as a result of the differences in the response of the ionosphere and plasmasphere to geomagnetic storm. Since plasmaspheric TEC distribution is not uniform and that the dominant contributions are found in the equatorial region (Yizengaw et al., 2008; Klimenko et al., 2014), significant data-model discrepancy may occur in location like Ilorin where knowledge of the plasmaspheric contribution to TEC during quiet and disturbed geomagnetic conditions is not well known.



**Fig. 7.** (a–c) shows the variation of the IRI-Plas modeled parameters as well as the average quiet and storm time variations at the station during the storm days of the 29 May 2010 geomagnetic storm event (d–f) shows the prediction errors of all the model options together with their respective average values for all the storm days considered.



**Fig. 8.** (a–c) shows the variation of the IRI-Plas modeled parameters as well as the average quiet and storm time variations at the station during the storm days of the 4 August 2010 geomagnetic storm event (d–f) shows the prediction errors of all the model options together with their respective average values for all the storm days considered.

## 5. Conclusion

The capability of the IRI-Plas model to predict the state of the ionosphere in a region like Africa that has no data representation in the build-up of global ionospheric models has been tested in this study. In our investigation, the IRI-Plas derived TEC and the F2-layer peak parameters (foF2 and hmF2) are compared to the observed values that are obtained at an African equatorial location during the 5 April, 2 May, 29 May and 4 August 2010 geomagnetic storm events. The model estimations of when operated with input of external data were compared to the “no input” representations. We found that the model reproduced TEC quite well when operated with GPS-TEC and GIM-TEC. However, with ionosonde derived foF2 input, there is significant discrepancy between the modeled TEC and the observed values for all the storm days. Overall, we found that the model with GPS-TEC input gives the best prediction of TEC. Also, with GPS-TEC input, the prediction error of the modeled TEC reduced

very significantly up to 1–3 times as compared to GIM-TEC assimilation. This difference can be attributed to the error due to the complex spatial interpolation routine in the estimation of TEC in the GIM cell. Furthermore, all the model options failed to reproduce the storm induced prominent features in both the foF2 and hmF2 structures in all the days considered. This indicates that the F2-layer peak parameter representations of the model with TEC (either from GPS or GIM) give a result that is still far from the real values. Therefore, the model representation using the no input option is still valid for the storm-time computation of the peak parameters.

## Declarations

### Author contribution statement

S.J. Adebiyi: Conceived and designed the experiments; Wrote the

paper.

S.O. Ikubanni, B.O. Adebesein, B.J. Adekoya: Analyzed and interpreted the data.

J.O. Adeniyi: Conceived and designed the experiments.

B.W. Joshua: Performed the experiments.

I.A. Adimula, O.A. Oladipo, A.O. Olawepo: Contributed reagents, materials, analysis tools or data.

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#### Competing interest statement

The authors declare no conflict of interest.

#### Additional information

Data associated with this study has been deposited at Global Ionospheric Radio Observatory (GIRO) database (<http://giro.uml.edu/didbas/e/scaled.php>) and IONOLAB space weather online interface service available at ([www.ionolab.org](http://www.ionolab.org)).

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