Responses to interactive comments on, **"Modeling Total Electron Content derived from radio occultation measurements by COSMIC satellites over the African Region"**

By Mungufeni et al.

February 7, 2020

We thank the anonymous referee for taking time to evaluate our manuscript. All the comments are addressed as shown below.

Comment:

The manuscript presents an empirical model describing ionosphere total electron content over African region. Authors use experimental TEC data obtained using dual frequency GNSS RO receivers onboard of COSMIC satellites to construct the model. They validate the model using same type of data that was used to construct the model but for a different period.

Response:

In addition to using the same type of data for validating our model, we shall also use TEC measured by ionosonde stations over South Africa. This is in line with comments made by another anonymous reviewer.

Comment:

General impression is that the present work has no contribution to the current understanding of the low latitude ionospheric physics/modelling. The work brings a little science and the newly created model could hardly be used in any real-life application. Authors are making too many assumptions and mistakes, sometimes trying to deliberately present performance results better than they are. Moreover, the performance of the model has not been compared to any other well-known model, leaving a room for doubts. Therefore, I recommend the manuscript (in its present form) is **rejected**. At the same time, the work might be improved and worth publication after substantial modifications. Please find below a list of critical issues along with possible improvements/corrections for a potential future re-submission.

Response:

Later comments reveal that the reviewer has kindly elaborated with examples the above comments. Therefore, appropriate responses have been given later following the elaborated comment. Since all comments have been addressed appropriately, we do not expect a decision to reject our manuscript.

Comment:

P.1 L.27: Replace “good” with “applied”. Otherwise, provide a proof of the model “goodness”

Response:

The suggestion will be implemented.

Comment:

P.2. L.35-38: Not all GNSS systems support ionospheric corrections. E.g. GLONASS does not broadcast any ionospheric model parameters. Correct the sentence accordingly.

Response:

The correction will be done as suggested.

Comment:

P.2 L.40: Provide a reference to the original description of Klobuchar model: *“Klobuchar JA (1987) Ionospheric time-delay algorithm for single frequency GPS users. IEEE Trans Aerosp Electron Syst 23(3):325–331. https://doi.org/10.1109/TAES.1987.310829”*

Response:

The reference will be added as suggested.

Comment:

P.2 L.41-42: NeQuick G model is based on the NeQuick model, but not NeQuick 2. Correct the statement and the reference accordingly, e.g. *"EC (2016) European GNSS (Galileo) Open Service—Ionospheric correction algorithm for Galileo single frequency users, Issue 1.2, Sept. 2016, European Commission"*

Response:

The correction will be done and the suggested reference will also be added.

Comment:

P.2. L.42: Change "The NeQuick is" to "The NeQuick and its subsequent modifications (NeQuick G and NeQuick 2) are"

Response:

The suggestion will be implemented.

Comment:

P.2 L.53: IRI model does not provide information about "electron and ion velocities". It only provides information about equatorial vertical ion drift. Correct the sentence accordingly.

Response:

The sentence will be corrected as, "For the international standard specification of ionospheric parameters (such as electron density, electron and ion temperatures, and ion drift velocity) …."

Comment:

P.2 L.55-56: Change "The model is primarily" to "IRI is an empirical model primarily"

Response:

The suggestion will be implemented.

Comment:

P.3 L.74: Change “GIM” to “global ionosphere model”, as GIM is already defined to be Global Ionosphere Map.

Response:

The suggestion will be implemented.

Comment:

P.3 L.76: Change “GIM model” to “global ionosphere model”

Response:

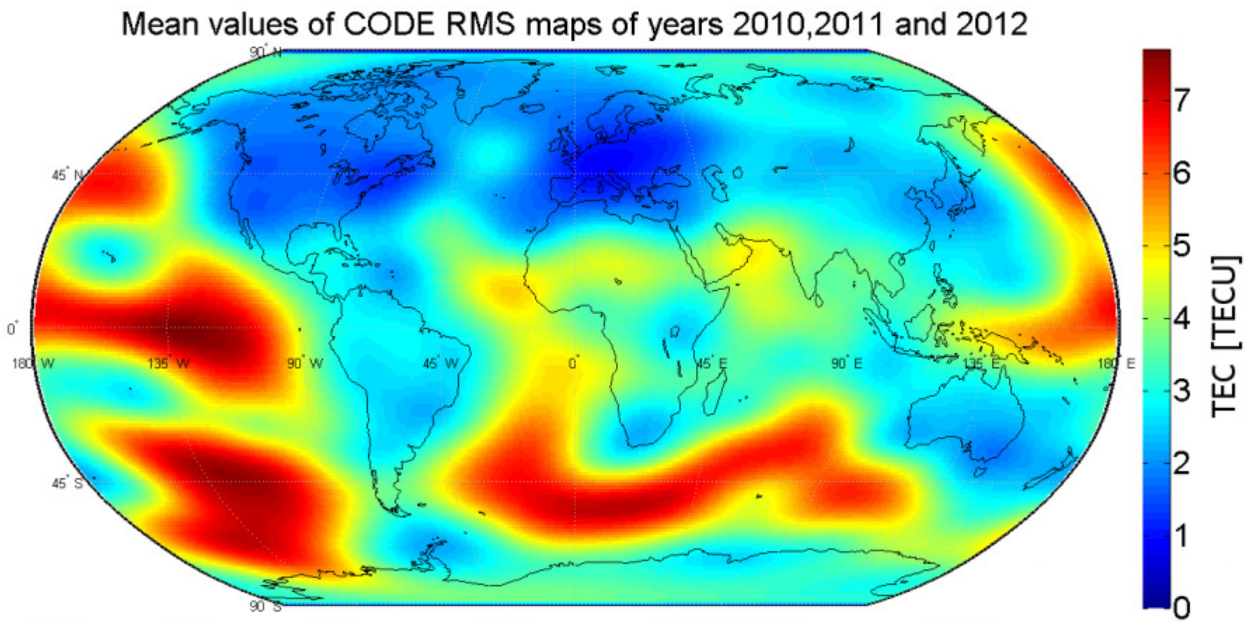
The suggestion will be implemented.

Comment:

P.3 L.80-82: The high values of RMS in low latitude region provided by CODE is, primarily, due to the inability of the selected model function (spherical harmonics) to describe ionospheric structure in low latitude. Modify the sentence accordingly.

Response:

We based on Fig below (obtained from Najman, P. and Kos, T.: Performance Analysis of Empirical Ionosphere Models by Comparison with CODE Vertical TEC Maps, Chapter 13, in: Mitigation of Ionospheric Threats to GNSS: an Appraisal of the Scientific and Technological Outputs of the TRANSMIT Project, InTech Open Science publications, pp. 162 - 178, doi:10.5772/58774, 2014) to make the statement, “This could be due to the poor distribution of IGS tracking stations over Africa and anomalies in the ionosphere related to the geographic and geomagnetic location”.



Indeed, figure above shows high RMS values over the oceans and land masses that have few/no ground based GPS receivers. This situation typically exists around and over the African continent.

Since figure above does not strictly show high values of RMS over all low latitude regions where EIA exists, we intend to remove EIA as a reason for the high RMS values over Africa.

Although the reviewer did not give reference, his/her suggestion of the inability of spherical harmonics to describe well low latitude ionospheric structure is consistent with existence of EIA over low latitudes.

Comment:

P.3 L.84: Change “the GIM model” to “global models”

Response:

The suggestion will be implemented

Comment:

P.4 L.115: Author use TEC integrated up to COSMIC satellite heights (800 km) to construct the model (*“integration being done up to the altitudes of the COSMIC* *satellites'*). However, the topside TEC values (according to numerous studies, e.g. by Bilitza 2009, Yizengaw 2008 etc.) can reach from 10% to 80% of the total electron content (from ground to GNSS satellite heights). This fact significantly reduces the scientific value and application of the developed model. Essentially, the model is useless for GNSS applications.

Response:

We are aware about the existence of substantial ionosphere above the altitude of COSMIC satellites. Concerning the region under study, the upper quartile of the differences between coincident COSMIC RO TEC and ground based GPS TEC could reach ~11 TECU (Mungufeni et al, (2019), *Characterization of Total Electron Content over African region using Radio Occultation observations of COSMIC satellites*, Adv in Space Res 65, 19 – 29). The problem is that such differences vary with location. To make it worse, over the oceans and some land masses such differences may not be established due to lack of ground based GPS TEC over such locations. In general, at the moment it is yet difficult to adjust COSMIC RO TEC to include plasmaspheric TEC. Due to these challenges, we do not trust usage of data from previous studies (e.g 1. Mungufeni et al. (2019), *Estimation of equivalent ground-based total electron content using CHAMP-based GPS observations*, Adv in Space Res 64, 199 – 210 and 2. Okoh, et al. (2019). A neural network based ionospheric model over Africa from COSMIC and Ground GPS observations. Journal of Geophysical Research: Space Physics, 124. https://doi.org/10.1029/2019JA027065) that attempted to scale space based GPS TEC to yield equivalent that would be obtained using ground based GPS TEC.

We thick that lack of inclusion of plasmaspheric TEC in COSMIC RO TEC, does not render the data completely useless. This point can be illustrated by examining the available differences between coincident COSMIC RO TEC and ground based GPS TEC. Since the upper quartiles of the differences can reach up to ~11 TECU, the median/mean values might obviously be much lower than this value. This might be the reason for observing most of the well known ionospheric TEC features over the African region when the COSMIC RO TEC were appropriately binned (Mungufeni et al, (2019), *Characterization of Total Electron Content over African region using Radio*

Occultationobservations of COSMIC satellites, Adv in Space Res 65, 19 – 29). The ionospheric features being referred to include; (i) occurrence of minimum and maximum TEC during 0:00–08:00 LT and 12:00–16:00 LT respectively, (ii) occurrence of secondary TEC enhancement (maximum) during 16:00–20:00 LT, (iii) lowest TEC values being observed in June solstice and highest TEC values observed in March equinox, (iv) TEC values increase as solar activity changes from low to high, (v) mid latitude TEC values are lower than those of low latitude regions, and (vi) occurrence of equatorial ionisation anomaly.

Therefore, the current model was built with the aim of simulating these known ionospheric features.

Comment:
P.5 L.124-126: This statement "*Since the magnitudes of the TEC obtained from COSMIC occultation 124 measurements are close to ground based GNSS TEC*", is not consistent with the previous statement and studies by Mungufeni et al. 2019. Where they show that, depending on the location, the RMS error can vary from 2 to 8 TECU and error distribution plots show values from -24 to 20 TECU. Such large errors cannot be considered "*close to ground-based GNSS TEC*". Authors, at least, are expected to provide information about relative TEC errors (in %, rather than TECU) to claim that errors can be tolerated (if so).

Response:

The response to this comment is similar to that of the previous comment. In particular, we shall mention in the manuscript that the average/median error might be much lower than 11 TECU.

Comment:
P.6 L.150: The title of the reference Emmert et al. 2010 is incorrect: *Emmert, J. T., Richmond, A. D., and Drob, D. P.: Statistical analysis of the correlation 412 between the equatorial electrojet and the occurrence of the equatorial ionisation 413 anomaly over the East African sector, J. Geophys. Res., 15; A08322; 414 doi:10.1029/2010JA015326, 2010.*

Response:

The correction will be made.

Comment:

P.6 L.157-167: The selected spatial resolution of 15º in longitude and 5-8º in latitude is too coarse to describe the ionosphere reasonably, especially for the low latitude region, where TEC is changing dramatically from the crest down/up to two peaks of EIA. E.g. GIM maps (the source of the data for most of the empirical models discussed by the authors in the introductions section) use at least 5º by 2.5º resolution (lon and lat). Moreover, 15º in longitude corresponds to 1 hour in LT. Gradients in TEC as a function of LT during sunrise and sunset hours may reach tens of TECU per hour (e.g. Mungufeni et al. 2019, Fig. 2). Therefore, such coarse spatial resolution in longitude will lead to big errors in the model description.

Response:

As already stated in the manuscript (page 6, lines 159 – 160) the problem that might arise when a smaller grid resolution is applied is data gaps in some grids. This problem was also illustrated to another anonymous referee. In the illustration, we showed that there are typically ~80 data points observed in a day over the study area. Obviously this number cannot cover all the 24 hours in a particular grid. The situation becomes worse when more grid shells are created. Therefore our choice of grid resolution ensured a balance between observing fairly fine ionospheric structures and created grid shells are not empty. Another method we used to ensure that the created grid shells are not empty is by binning our data according to 3 different ranges of solar flux levels, instead of binning data according to year.

Although our choice of grid resolution appears to be coarse, we were able to observe the previously mentioned known ionospheric features over the African region. This confirms that the justifications we have given for the choice of 15^{o} longitude (page 6, line 163) and the various latitudinal values (page 6, line 158 and lines 164 - 165) are logical. We have noted a mistake on page 6, line 164. The phrase should be, "… the latitudinal grid resolution was reduced 5^{o} for dip latitude range ….."

Comment:

P.6 L.170: The whole solar cycle 24 has relatively low solar activity level compared to the two previous ones. Nevertheless, even if we look only at the 24th solar cycle, 2011 and 2016 could hardly be attributed as years of high solar activity level. Please, modify the statement accordingly (e.g. as it is done on P.7 L.182).

Response:

The suggestion will be implemented

Comment:

P.7 L.189: Please clarify, how 36 solar flux bins were obtained. From the description, it is only 3 solar flux ranges and 12 months, that gives 36 (3x12). But when listing by a variable, only number 3 has to be specified, as it is done, for example with the rest of the variable (hour, lat and lon). Indeed, if we take 60,480 TEC values indicated in L.189, this number can be obtained by multiplying 5x14x3x12x24, but not 5x14x36x12x24.

Response:

In each range of solar flux level, there are 12 nodes, corresponding to the months in a year. We shall state this explicitly in the manuscript

Comment:

P.8 L.205: According to the definition of cubic spline, it is a spline constructed of piecewise thirdorder polynomials, meaning none of the B splines used in the model were cubic (order 2 and 4). Change the "cubic B spline" into "B spline of different orders" throughout the text and abstract.

Response:

The suggestion will be implemented in the manuscript

Comment:

P.9 L.218-220: Consider changing this sentence to something like "In order to assess the ability of the model to describe the data used to construct the model, modelled data were compared to the experimental one. The results of the self-consistency check are presented in Figure 1."

Response:

This suggestion will be implemented in the manuscript

Comment:

P.9 L.228-229: It is surprising that the authors compare the results of the climatological model (i.e. model where input data were averaged over time, e.g. one month) with GIM map for a single day of that month. Such a comparison is not correct. On top of that, by looking at TEC maps obtained from COSMIC and later by B spline model (columns 2 and 1), one can hardly see any separation between the peaks of the EIA, that can, taking into account averaging in all the bins (e.g. lat and lon) performed by authors, hardly be comprehended.

Response:

The GIM-TEC panel will be removed. This will give more space to include comparisons with other models and ionosonde data

We can see clear separation between the crests of EIA before 17:00 LT. However, after this time (sun set) the crests appear to merge. This is expected as the direction of the zonal electric field reverses at around sunset.

Comment:

P.9 L.231-232: By looking at the color plots, a reader can hardly assess the performance of the model. It is suggested, in addition to the plots, to present/discuss the results of the mismodelling in terms of a bias and RMS of the error.

Response:

The first intention of presenting figures 1 and 2 was to make readers appreciate the ionospheric features that can be revealed by the data used for modeling. Indeed, we observed and discussed features such as diurnal, seasonal, and solar flux level dependence to mention.

The second intention was to show that the B spline functions can trace very well the trends in the data used for modeling. Surely, observation of two panels from the same row, but different columns reveals that the B spline function traces the trends in measured data very well.

We would like to mention that detailed validation of our model using independent data was presented in figures 3 and 4. We intend to also validate our model using TEC measured by ionosonde stations over South Africa (a suggestion by another anonymous reviewer).

Comment:

P.10 L.250-252: From Fig 1 it cannot be clearly understood the secondary maximum if any, especially at -20 lat. Please, if you discuss a feature, try demonstrating it clearly to the reader. A separate figure, or at least, a dashed line at -20 and 4 in Fig 1 is needed to support the statement.

Response:

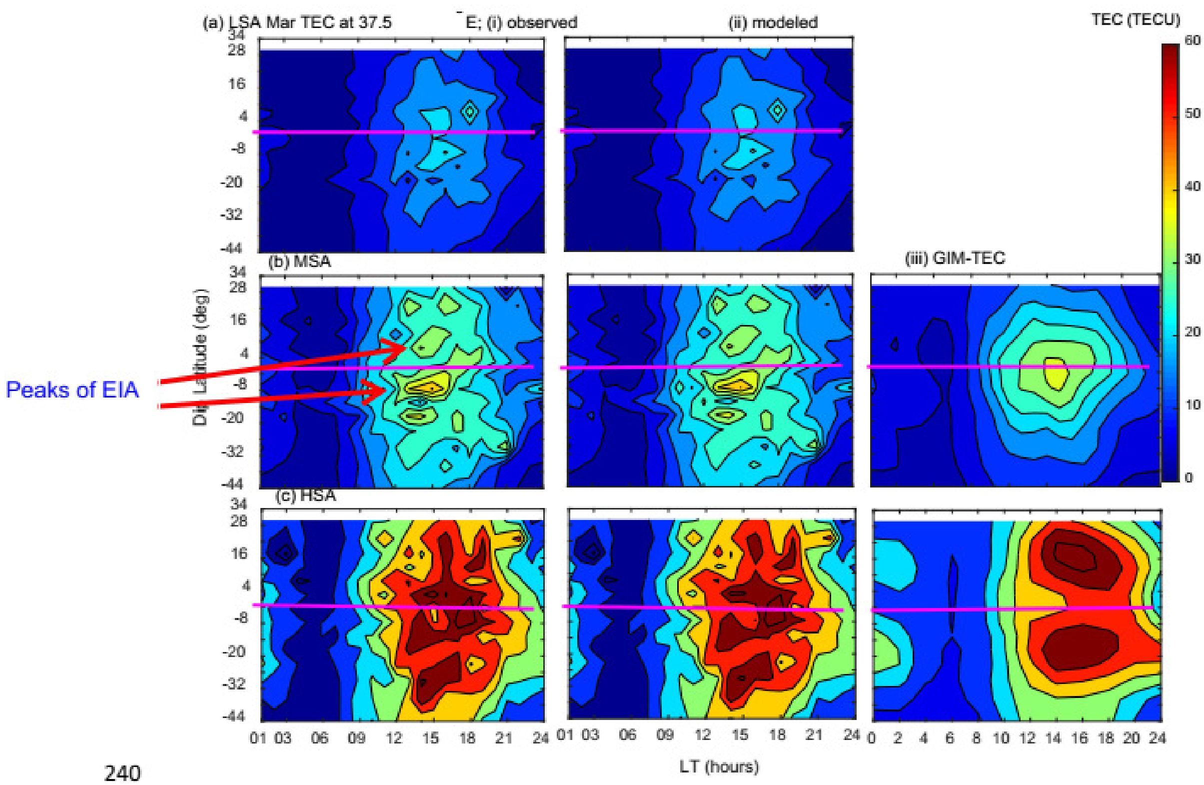
This suggestion will be implemented

Comment:

P.11 L.269-270: In row (b), Fig 1, none of the panel show peaks of the EIA. There is no clear separation of the crest and peaks of EIA. Nor in panels b1/b2 neither in b3. Modify the sentence accordingly.

Response:

Using red arrows, we have illustrated in figure below the peaks of the EIA. Attention was given to panels in row (b). The question about separation of the peaks was also raised earlier and it was answered.

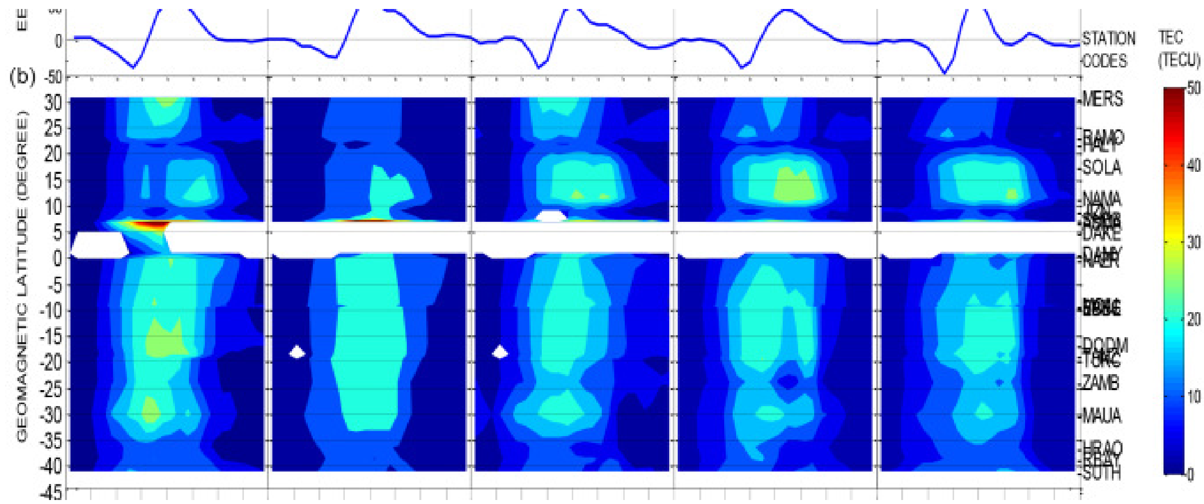


Comment:

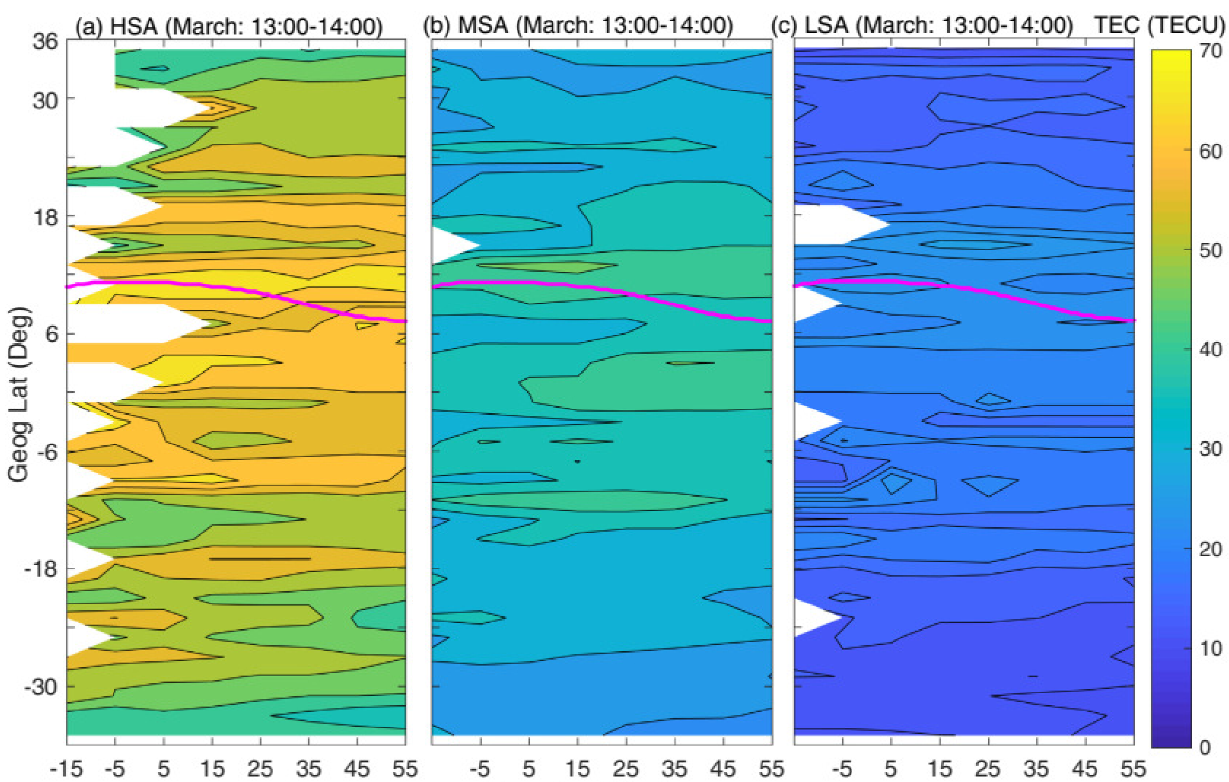
P.277-279: The structure of the crest might differ based on various factors (including level of the geomagnetic disturbance). However, when taken as an average, a clear 2 peak structure is present in low latitudes, representing EIA.

Response:

Figure below (Bolaji, et al. 2017. Observations of equatorial ionization anomaly over Africa and Middle East during a year of deep minimum, Ann. Geophys., 35, pp. 123 – 132, 2017) taken during a deep solar minimum still shows several crests of EIA. It should be noted that the horizontal axis represents local time. The figure clearly shows in first panel two crests south of the dip equator.



Another figure showing several crests on either side of the dip equator is below (Mungufeni et al, (2019), *Characterization of Total Electron Content over African region using Radio Occultationobservations of COSMIC satellites*, Adv in Space Res 65, 19 – 29).



Details about the data plotted in panel (a) which clearly shows several crests are as follows. The data consists of average COSMIC RO TEC during 13:00 – 14:00 UT. The data were for 67 quiet days in March (2008 - 2015). The F10.7 flux on the days were >120 sfu. The spatial binning resolution was 10^{o} in longitude and 2^{o} in latitude. The data gaps mentioned previously can be seen due to the reduced binning resolution.

To verify these observations of several crests on either side of the dip equator, we might need in situ measurements of electron density by polar orbiting satellites flying at altitude range of 120 – 400 km.

Comment:

P.12 L.298-299: The science question in this case is not how to model the observed data, but how to explain the data. What is the physical explanation for the absence of the EIA structure (two peaks and the crest) in TEC values calculated from the ground up to COSMIC satellite heights (~800km). And whether this phenomena is not a limitation of the technique applied to calculate TEC. Namely, TEC computed by integrating electron density profile, that by itself is a product of RO inversion, is subject to big errors, especially in places where big horizontal gradients exist (read, e.g. M.M Shaikh et al., Implementation of Ionospheric Asymmetry Index in TRANSMIT Prototype, DOI: 10.5772/58551). Without understanding the reasons of the observed behavior all the modeling efforts are meaningless.

Response:

In the paragraph under question, we mentioned asymmetry of EIA feature and occurrence of secondary peak in TEC over Africa. We further mention that these features can be seen in the data we used to develop our model. Therefore, our model emulates these features. We would like to mention that these two features have been well explained in the manuscript (see page 11, lines 256 – 27 and page 12, lines 284 - 286).

The reviewer's phrase, "absence of the EIA structure (two peaks and the crest) in TEC values calculated from the ground up to COSMIC satellite heights (~800km)" does not exist in our manuscript. This makes it difficult for us understand the point the reviewer would like to make. Anyway, we guess that the reviewer is talking about absence of asymmetry of EIA feature in GIM-TEC. In case this is correct, the first reason might be poor distribution of ground based GPS receivers over the African region. The second reason as previously stated by the reviewer might be inability of the spherical harmonic function to map TEC over the low latitude regions. We already provided the first reason on page 11, line 253, we shall add the second reason to the manuscript.

Comment:

P.13 L.313: One cannot see the "perfect match" of the observed and modelled data just by looking at the plots. At least a third row in form of difference map (error map) has to be presented to visually assess the error level. Moreover, statistical results (e.g. RMS and bias of the error) must be presented in order to make such a bold conclusion.

Response:

We kindly request the reviewer to have another look at figures 1 and 2, taking for instance two panels from the same row, but different columns. After appreciating the perfect match between the observed and the modeled data, there would be no need for error map.

On the other hand, we understand the importance of error maps, particularly when validating a model with independent set of data. We demonstrated this by presenting figure 4.

Comment:

P.13 L.312-324: Authors do not discuss at all the TEC behavior observed in September at lat ~ -20, where its diurnal variation has a maximum during local night hours (21-03 LT). This maximum seems to exceed any other TEC values on this plot (row c, column 1 and 2) and looks like an error in the data processing. Such behavior seems to have no physical explanation.

Response:

On page 13, line 313, we stated that, "among the many features of TEC exhibited …." This means we were interested in the key features. Now that the reviewer has identified a possible out liar during September at lat ~ -20^o, we agree to mention the same in the manuscript.

Comment:

P.14 Section 5: The authors fail to explain why they need yet another TEC model. Unless the performance of the newly created model is compared to existing models and it is demonstrated that its any better than the rest of the models present on the "ionosphere model market" (e.g. IRI, NeQuick, NTCM etc.), there is very little value in the study (both scientifically and application-wise).

Response:

We shall compare our model with the existing models such as IRI and NeQuick, and AfriTEC (Okoh et al. 2019).

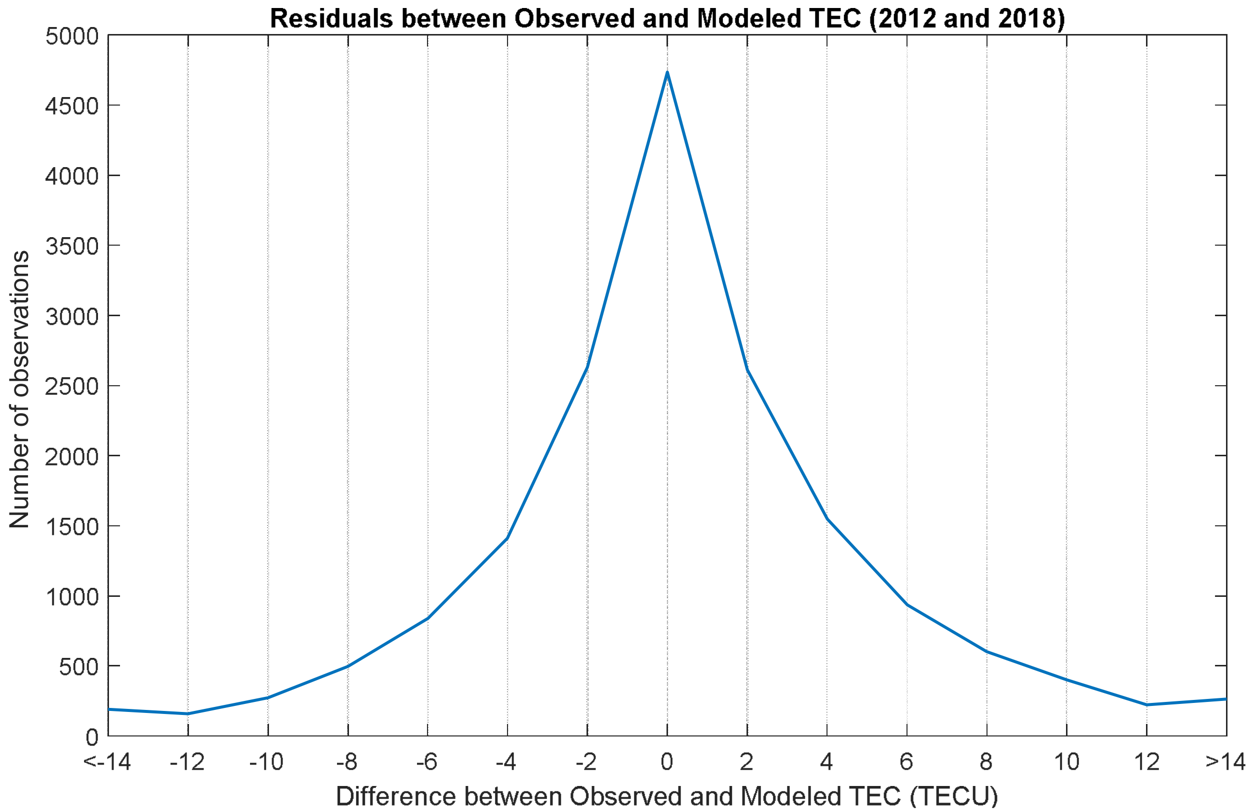
Comment:

P.15 L.350-353: Figure 4 does not show the full picture of the error distribution. It is clearly cut at -14 and 14 TECU. Iif one looks at Figure 3, errors in TEC can easily reach +-20 TECU (just draw a vertical line at any value of Observed TEC, e.g. at 30 TECU). It looks like the authors deliberately try to improve the results of their model performance.

Response:

Actually, we should have not indicated ±16 on the horizontal axis. Moreover, we should have indicated on the horizontal axis < -14 (instead of merely -14) and > 14 (instead of merely 14). The total number of errors with values in the range of -14 – 14 TECU was 16858 (97.4 %), while the number of errors with values outside this range was 454 (2.6 %). By comparing these two percentages, it can be deduced that the number of errors with values outside the range of -14 – 14 TECU was insignificant. In statistics, conclusions are made based on majority, but not minority.

After implementing the above changes, Figure 4 would appear as below



Minor/Typo comments:

P.1 L.17: Change “derived” to “obtained”

P.1 L.19: Change “Geomagnetically quiet time (Kp < 3 and Dst > -20 nT) data during the years” to “Data during geomagnetically quiet time (Kp < 3 and Dst > -20 nT) for the years”

P.1 L.22 Change “to obtain the model” to “to obtain model coefficients”

P.1 L.26 Change “COSMIC TEC” to “COSMIC RO TEC”

P.2 L.31: Change “using Global Navigation Satellite Systems” to “in Global Navigation Satellite Systems”

P.2 L.30 Change “during day” to “during the day”

P.2. L.49: Space is missing between “European Geostationary”

P.2 L.50: Change “GPS And Geo-Augmented Navigation” to “GPS-aided Geo Augmented Navigation”

P.3 L.63: Space is missing in “analysis centers”

P.3 L.64: Space is missing in “using the”

P.3 L.64: Change “Global Ionospheric TEC data Map (GIM)” to “Global Ionosphere Maps (GIMs)
containing vertical TEC data”

P.3 L.66: Change “Global Ionospheric TEC data Maps (GIMs)” to “GIMs”. It has been defined two linesabove.

P.3 L.70: Space is missing in “the average”

P.3 L.71: Space is missing in “by CODE”

P.3 L.76: Space is missing in “constructed a”

P.3 L.77: Space is missing in ”GPS radio”

P.3 L.82: Space is missing in “related to”

P.4 L.87: Change “localized ionospheric structure” to “localized ionospheric structures”

P.4 L.88: Change “on a global scale model” to “in global models”

P.5 L.140: Space is missing in “during geomagnetically”

P.6 L.147: Change “solar activity” to “solar activity level”

P.6 L.164: Remove “15” in “reduced 15 to 5”

P.7 L.181 Space is missing in “the F10.7”

P.9 L.223: Change “Global Ionosphere Map (GIM) TEC (GIM-TEC)” to “GIM TEC”, as it was defined earlier, remove “Center for Orbit Determination in Europe” – it was defined earlier

P.9 L.225-226: Remove “The daily GIM-TEC values are derived using the GNSS data collected from over 200 tracking stations of IGS and other institutions”, as this information was given earlier in the text

P.10 L.238: Space is missing in “in turn”

P.14 L.336: Change “;” to “:”

P.14 L.337: Space is missing in “root mean squared”

P.17 L.373: Change “:” to “.” In “0.93”

Response:

All minor comments will be addressed as suggested by the reviewer