Response to Reviewer#RC1

Comment 1
Equation (1): Did it require to include a mean term?

Response
Thank you for the inquiry. A mean term is not required. Singular Value Decomposition factorizes a matrix $M_{m\times n}$ into three other matrices U, S and V as given in Equation 2. To recover $M_{m\times n}$, we take the matrix product of U, S and V. The $\sum_{j=1}^{n}$ in Equation 1 is for the sum of the product of the matrix entries in the multiplication of U by C, where C is given by Equation 2.
Comment 2
Page 3: Line 37: I cannot see the secondary maximum at about 20:00 UT from the Figure

Response
Thank you for the observation. Critical analysis of Figure 1 (a) shows that there is no secondary maximum at about 20:00 UT as we had earlier stated. What appears at about 20:00 UT is an enhancement. The sentence was therefore rephrased to: Figure 1 (a) shows that the average diurnal TEC (red curve) over Malindi has a pre-dawn minimum at about 03:00 UT, a maximum at about 11:30 UT and an enhancement from 18:00 to 20:00 UT. The maximum at 11:30 UT is possibly due to increased ionization as the solar zenith angle is nearly zero over Malindi around this time. The post sunset increase in the TEC from 18:00 to 20:00 UT could be due to an enhancement in the eastward electric field before its westward reversal at night. This appears in page 4 lines 7-10

Comment 3
Figure 1: What is the red curve? No words are given.

Response
Thank you for the observation. What the red curve represents has now been clearly stated in the caption. The caption of Figure 1 was therefore changed to:
The first six basis functions (a) representing the diurnal variation and their coefficients (b) which show the long-term variation of TEC over MAL2. The red curves in the top left panels in (a) and (b) compare the diurnal mean TEC with the first basis vector U1 and the solar radio flux index measured at 10.7 cm wavelength (F10.7) with coefficients C1 of the first EOF mode respectively.

Comment 4
Page 4, Line 16: The statement is incorrect. Periods of 0 is not the linear variation.

Response
We acknowledge that a linear function is not of period zero. In fact, a linear function has infinite period. We have deleted the incorrect statement and then updated the sentence in page 5 lines 14-19 to page 6 lines 1-5 as follows.

We then expressed the EOF coefficients as a sum of linear and harmonic functions following the procedure of Zhang *et al.* (2009) as

$$\mathrm{C_j(d) = B_{j1}(d) + B_{j2}(d) + B_{j3}(d)} \tag{1}$$

The term $\mathrm{B_{j1}(d)}$ is to account for the linear variation of the EOF coefficients with solar and magnetic activities and is given by

$$\mathrm{B_{j1}(d) = a_{j1} + b_{j1}F10.7_{av}(d) + c_{j1}Dst(d)} \tag{2}$$

The semiannual and annual variations in the EOF coefficients are represented in equation 1 by the harmonic terms $\mathrm{B_{j2}(d)}$ and $\mathrm{B_{j3}(d)}$ of periods half a year and 1 year (365.25 days) respectively expressed as

$$\mathrm{B_{j2}(d) = \left[a_{j2} + b_{j2}F10.7_{av}(d) + c_{j2}Dst(d)\right] \cos\left(\frac{2\pi d}{365.25}\right) + \left[d_{j2} + e_{j2}F10.7_{av}(d) + f_{j2}Dst(d)\right] \sin\left(\frac{2\pi d}{365.25}\right)} \tag{3}$$

$$\mathrm{B_{j3}(d) = \left[a_{j3} + b_{j3}F10.7_{av}(d) + c_{j3}Dst(d)\right] \cos\left(\frac{4\pi d}{365.25}\right) + \left[d_{j3} + e_{j3}F10.7_{av}(d) + f_{j3}Dst(d)\right] \sin\left(\frac{4\pi d}{365.25}\right)} \tag{4}$$

Comment 5
Equation (4): Why such presentation is reasonable or enough. No words to support it, no references are cited.

Response
We have provided in page 5 line 15 the reference by Zhang et al.(2009) in support of the method.

Comment 6 a
Equation (5): Same to Equation (4). Moreover, (1) F10.7 in Equation (5) and F10.7av in Equation (6)

Response
Thank you for the observation. In equation (5) it should have been F10.7av not F10.7. This was a typing error and has been corrected to:

$$\mathrm{B_{j1}(d) = a_{j1} + b_{j1}F10.7_{av}(d) + c_{j1}Dst(d)}$$

Comment 6 b
Is it enough to present the geomagnetic activity condition with Dst?

Response
(i) The Dst is based on measurements at near equatorial magnetic observatories (Honolulu, San Juan, Hermanus and Kakioka) and therefore it predominantly gives an indication of the equatorial ring current variations. Therefore Dst is more appropriate than AE since the observations are equatorial rather than auroral.
(ii) The Dst and Kp indices are not independent, so the best of these would be the one that gives the highest correlation with the TEC observations. Of the three magnetic indices considered, it is Dst that showed the highest correlation with the coefficients of the first EOF mode

Table RC1: Correlation of the expansion coefficients with some of the commonly used solar and magnetic indices. In brackets are the coefficients at a lag of one day

	Solar indices			Magnetic indices		
	SSN	F10.7	$F10.7_{av}$	Kp	AE	Dst
C1	71.2	75.8	79.1	19.0 (18.8)	15.6 (15.1)	-23.1 (-23.0)
C2	36.6	35.4	37.2	9.5 (8.7)	12.1 (10.0)	-5.5 (-6.0)
C3	16.9	16.7	16.4	4.2 (7.2)	4.6 (9.1)	-4.1 (-1.6)
C4	4.4	7.5	8.1	17.8 (14.4)	20.1 (18.4)	-13.3 (-4.0)
C5	5.8	6.9	7.0	2.3 (0.3)	1.3 (0.2)	-6.8 (-6.5)
C6	0.2	1.9	1.8	1.8 (0.7)	3.9 (1.8)	-4.4 (-3.1)

which explained 96.8% of the TEC variance over MAL2.

Comment 6 c
Is the linear relation between TEC and Dst sufficient?
Response
Numerous studies have used linear terms of solar and magnetic indices (e.g. Lastovicka et al.(2017), Uwamahoro and Habarulema (2015), Ercha et al 2012, Zhang et al 2009) to model TEC. More so, our data set did not reveal either a second or higher order relation between the daily averaged TEC and Dst, but rather a weak linear relation. Based on the observations with our data set, we adopted the linear relation in our model.

Comment 6 d
Is there no time delay between the occurrence of a geomagnetic storm and its effect on the ionosphere?
Response
Scherlies and Fejer (1997) observed that the equatorial plasma responds to high latitude current disturbance in time scales of 1-12 hrs (short-term effect) and 20-30 hrs (long-term effect). Owing to the fact that we are using daily averages of Dst, the short term effect can not be considered in the modeling process. To investigate the long term effects, we determined the correlation between the EOF coefficients and the magnetic indices at zero and one day lags. Our correlation analysis (see Table RC1) did not reveal significant differences in the correlation coefficients at zero and one day lags. In fact the daily Dst values showed slightly higher correlation coefficients at zero lag with the EOF coefficients except for the second EOF mode. Based on these observations, we used the daily Dst values with zero lag to model the EOF coefficients. As mentioned earlier, such a representation has also been used by many authors (eg Lastovicka et al 2017, Uwamahoro and Habarulema (2015), Ercha et al 2012, Zhang et al 2009) to model TEC.

Comment 6 e
How to simulate/reproduce the solar effect of TEC is essential for successful model TEC and further estimate the trend of TEC. In this work, the solar index uses F10.7 av. It did not provide references (suggest to cite two key works, Richards et al., 1994: Richards, P. G., J. A. Fennelly, and D. G. Torr (1994), EUVAC: A solar EUV flux model for aeronomic calculations, J. Geophys Res., 99, 8981-8992; Liu et al., 2006: Liu, L., W. Wan, B. Ning, et al. (2006), Solar activity variations of the ionospheric peak electron density, J. Geophys. Res., 111, A08304,

doi:10.1029/2006JA011598).

Response

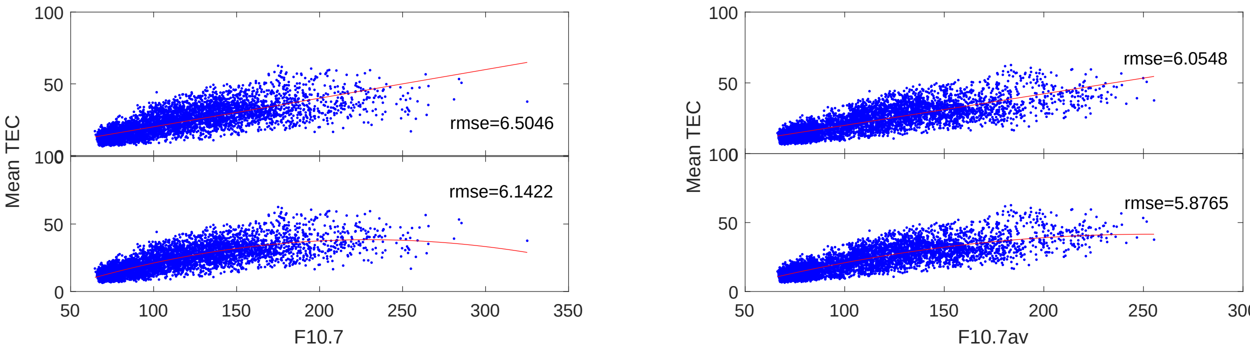
Thank you for the suggestions. Appropriate references provided in page 5 line 10 were cited as suggested

Comment 6 f

According to the investigation of Liu and Chen (2009) and Liu et al. (2009), the TEC is better to present as a second-order polynomial with F10.7, especially under the situation for estimating trend. References: Liu, L., and Y. Chen (2009), Statistical analysis on the solar activity variations of the TEC derived at JPL from global GPS observations, J. Geophys. Res., 114, A10311, doi:10.1029/2009JA014533. Liu, L., W. Wan, B. Ning, and M.-L. Zhang (2009), Climatology of the mean TEC derived from GPS Global Ionospheric Maps, J. Geophys. Res., 114, A06308, doi:10.1029/2009JA014244

Response

Thank you for the suggestion. We investigated the relationship between the daily mean TEC



(a) (b)

Figure RC1: Scatter plots for (a) daily mean TEC and F10.7 (b) daily mean TEC and F10.7av

and F10.7av. As suggested by Liu et al. (2009), representing F10.7 as second order polynomial has smaller root mean square error (see Figure RC1). The difference in rmse in using a linear fit and that of second order polynomial appears to be small especially with F10.7av.

We further proceeded to model the TEC by representing F10.7av as second order polynomial using the equations below.

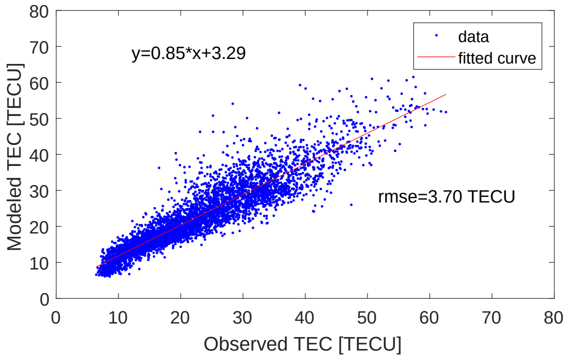
$$\mathrm{C_j(d) = B_{j1}(d) + B_{j2}(d) + B_{j3}(d)}$$

where

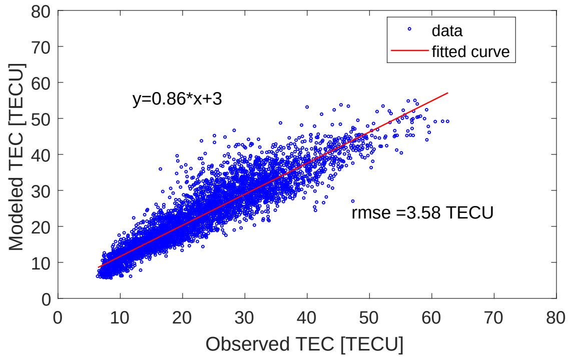
$$\mathrm{B_{j1}(d) = a_{j1} + b_{j1}F10.7_{av}(d) + c_{j1}[F10.7_{av}(d)]^2 + d_{j1}Dst(d)}$$

$$\mathrm{B_{j2}(d) = \left[a_{j2} + b_{j2}F10.7_{av}(d) + c_{j2}[F10.7_{av}(d)]^2 + d_{j2}Dst(d)\right]\cos\left(\frac{2\pi d}{365.25}\right) + \left[e_{j2} + f_{j2}F10.7_{av}(d) + g_{j2}[F10.7_{av}(d)]^2 + h_{j2}Dst(d)\right]\sin\left(\frac{2\pi d}{365.25}\right)}$$

$$\mathrm{B_{j3}(d) = \left[a_{j3} + b_{j3}F10.7_{av}(d) + c_{j3}[F10.7_{av}(d)]^2 + d_{j3}Dst(d)\right]\cos\left(\frac{4\pi d}{365.25}\right) + \left[e_{j3} + f_{j3}F10.7_{av}(d) + g_{j3}[F10.7_{av}(d)]^2 + h_{j3}Dst(d)\right]\sin\left(\frac{4\pi d}{365.25}\right)}$$



(a)



(b)

Figure RC2: Scatter plots for observed TEC and modeled TEC using (a) F10.7av as a linear term (b) F10.7av as a second order polynomial

Figure RC2 shows that representing the solar activity as a second order polynomial results in smaller error than using the linear relationship. However, the difference in the rmse appears insignificant and we think will not result in any substantial differences in the conclusions

Comment 7

Figure 2: An equation is welcome to give the regression. I am curious as to why there is a significant intercept.

Response

A regression equation has been included in Figure 2 (d) as shown in Figure RC3. A positive

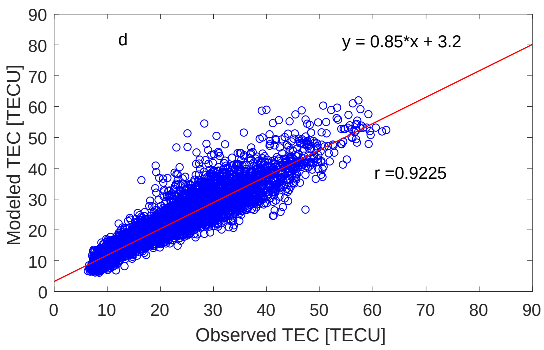


Figure RC3: Correlation between the daily averages of the modeled TEC and GPS TEC over MAL2.

bias is observed in the Modeled TEC. The reason for the positive bias in the modeled TEC is not known.

Comment 8

Figure 4: The case on 07/11/2004 has no observation of GPS-TEC. If so, what is the value to include it here.

Response
We have updated Figure 4 and replaced Figure 4 b with another where GPS TEC was available

Comment 9
Figure 6: What are the white curves? So are those in Figures 8 and 10

Response
The horizontal curved solid white lines in (a) show the geomagnetic dip equator. The dashed white lines show the anomaly region at $\pm 15^o$ geomagnetic latitude from the dip equator. This has been made clear in the captions of Figures 6, 8 and 10

Comment 10
Page 12: Line 5: Since the processing of TEC may introduce biases to TEC, my question is how about the possible influence of your TEC on the trend?

Response
It is correct that the background TEC may influence the magnitude of the trends. The good correlation between our TEC (Equation 1) and the GPS TEC over Malindi make it suitable to be used as a background in trend studies. There could be a bias due to the slight change in the position of the receiver from 40.19439° E, 2.99591°S to 40.19414°E, 2.99606°S. However, the agreement (in sign) in the trends from the global ionospheric maps with that from the GPS TEC (see Figure 9 b) imply the effect of the slight change in receiver's position may be insignificant.

Comment 11
Figure 10: An issue is the influence of different presentation of solar dependency of TEC, linear or higher order on the trend. According to the investigation of Liu and Chen (2009) and Liu et al. (2009), the TEC shows saturation in equatorial regions, such a linear presentation as in this work will introduce what influence on the estimated trend?

Response
Thank you for the comment. As mentioned earlier, the second order representation of the F10.7av in modeling of the TEC over Malindi resulted in lesser rmse. We implemented the second order representation of F10.7av in estimating the TEC trends over Malindi for the period 1999-2017. Trend values of 0.1812 ± 0.059, -0.112 ± 0.0606 and -0.0509 ± 0.0818 were obtained for GPS TEC, CODE's TEC and TEC from JPL ionosphere maps respectively. When F10.7av is represented as a linear term, trend values of 0.139 ± 0.063, -0.119 ± 0.061 and -0.057 ± 0.042 were obtained for GPS TEC, CODE's TEC and TEC from JPL ionosphere maps respectively for the same period 1999-2017. The trends derived from the two approaches do not show a significant difference, and therefore the pattern of the trends shown in Figure 10 will not change.

Comment 12
Page 11, Lines 18-21: The trend is positive. In contrast, in other works it is negative. What causes the difference?

Response

Thank you for the question. We are not aware of any study that has reported negative TEC trend over Malindi though negative trends in foF2 and hmF2 have been observed in other geographical regions where long records of ionosonde data exists. The only study that has reported a slight negative trend in TEC is by Lastovicka *et al.* (2017). The slight negative TEC trend reported in Lastovicka *et al.* (2017) was for the global TEC. The differences in the results of Lastovicka *et al.* (2017) and our work could be due to:

i) The different data sets used. Lastovicka *et al.* (2017) used global averages of TEC derived from 35 continuously operating stations.

ii) The difference in the geographical regions. The drivers of ionospheric trends may evolve differently over the different geographical regions.

It is worthy to note that the positive TEC trend over Malindi (geographic coordinates 40.194°E, 2.996°S) reported in this study is consistent with the observation of Lean *et al.* (2011) (see Figure 7 in Lean *et al.* (2011)).

Comment 13

According to Equation (1) and Equation (4), there is expected that we can estimate the trend as different local times. My next question is how about the local time variation of the trend of TEC??

Response

We have calculated the local time variations in the TEC trends and this is Figure RC4. We think the night time trend magnitudes may be influenced by our background model owing to the fact that the major driver of TEC variability is changes in the solar radiation. The daily solar EUV proxy, F10.7 may not capture very well the ionospheric variability at night resulting in high relative percentage error in the modeled TEC at night. However we intend to include this in a follow paper that is to examine the diurnal and seasonal variation in ionospheric trends from both ground and space observations.

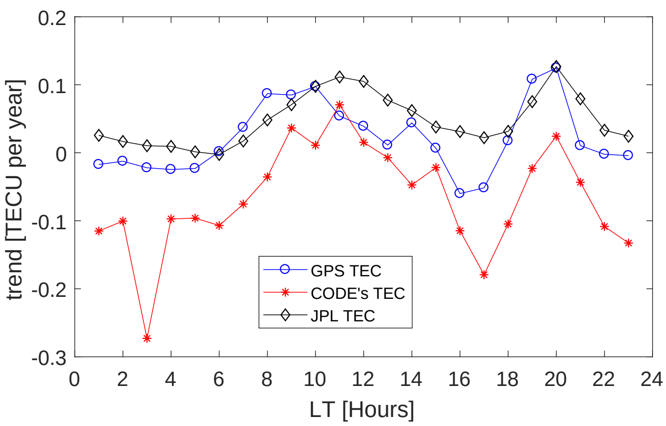


Figure RC4: Diurnal variation of TEC trends over MAL2 in the period 2003-2017

Response to review comments #RC2

Major comments

Comment 1: EOF analysis has been applied to TEC/foF2 modeling in low and middle latitudes, during geomagnetically quiet and storm conditions, and at regional/global scale (References below). In my point of view, the presented work seems to be a repetition of what has been done previously and its contribution towards research progress referring to existing works is not clear. I am suggesting the authors to revise the introduction and include the references provided above and then highlight briefly and concisely their contribution to research progress.

Response: It is true that similar work especially with the modeling technique has been done for other regions. A number of the references suggested have been included in section 3. The focus of this work is on regional trend estimation, and hence the contribution of this work is in terms of using the EOF model as a background in trend estimation and the nature of the trends over the African region. The need for such a study has been stated in the last paragraph of the introduction in page 2 lines 33-35 and page 3 line 1-3.

Comment 2: (Page 2, lines: 18 - 19). The authors mention that 2-hour GIM data was interpolated to 1-hour data and it is evident that during interpolation some errors are introduced. I am suggesting the authors to clarify how the interpolation method used in this study has been validated before being applied, and how errors due to interpolation will affect TEC modeling results.

Response: Given the different times for CODE's GIMs (odd hour before 2002, even hours from 2002-2014 and hourly after 2014) it was necessary to interpolate the data to provide a uniform sampling. Before the interpolation, we first extracted the VTEC for each longitude-latitude pair. The VTEC was then interpolated in time domain using linear interpolation. The choice for the linear function was because:

- Piece-wise linear functions are used for representation in the time domain while generating GIMs. This information is in the header of the data files
- Linearly interpolated CODE's GIMs have been validated with TOPEX/Jason TEC data (Jee *et al.*, 2010).

Since the basis vectors give the average daily trend over the entire period (1999-2017), we do not think that the choice of linear interpolation of the VTEC would substantially affect the model. In case of daily random errors due to the interpolation procedure, they will manifest in the higher order EOF modes, and these were discarded when modeling the TEC.

Comment 3: Discussion of the results and conclusions should be revised. The authors should highlight the main findings of the current work referring to previous works.

Response: Some of the major findings of this work include;

- The EOF-based TEC model provides a better background TEC over Malindi than the IRI. This is stated in page 11 lines 3-5 and page 15 lines 9-11
- Trend of TEC over MAL2 is positive. This has been stated in page 14 line 5.

- Confirmation of latitudinal variation in trends of TEC over African low latitudes and of negative trends dominating over the geomagnetic equator. This is stated in page 16 lines 8-10.

Minor comments

Comment 1: (Page 3, line 33) The six EOF modes are not elements of the matrix U as stated by the authors. Please remember that EOF modes ($U_j \times C_j$), EOF basis functions U_j and EOF coefficients C_j are different.

Response: Thank you for the observation. The sentence was rephrased to:
The basis vectors of the first six EOF modes in matrix U and their corresponding coefficients obtained using equation 3 are shown in Figure 1. This appears in page 4 line 6

Comment 2: (Page 4, lines 4 - 7) "The fluctuations ... dynamics". I disagree with this statement. Please refer to the above suggested works and explain correctly what the basis functions U j , j = 2, ..., 6 are describing.

Response: Since the basis modes represent the contribution of each factor in influencing the variability in the data, their ordering may vary for the different data sources. For example, according to Dabbakuti and Ratnam (2017), the second and third order basis function represent the semidiurnal variation associated with the summer to winter annual variation and ionospheric anomaly feature due to prereversal enhancement respectively. However, Dabbakuti and Ratnam (2016) observed that the second and third order base functions describe the variability due to irregularities and scale disturbances. While for our data, the second basis function appears to be associated with prereversal enhancement. It is important to note that, the physical interpretation of the basis functions are normally difficulty due to their geometric nature (Hannachi *et al.*, 2007). To avoid subjective interpretation of the basis functions, we have deleted the sentence "The fluctuations observed in the higher order basis functions could be signatures of the different processes (such as traveling thermospheric disturbances (TADs)) that influence the low latitude plasma dynamics" since no statistical analysis was done for the higher order basis functions.

Comment 3: (Page 4, Figure 1 (a) and (b)) Please clarify in the text that the top left panels of Figure 1 (a) and Figure 1 (b) compare diurnal mean TEC with U1 and solar flux index with C 1 , respectively.

Response: Thank you for the suggestion. The following sentence was added in the caption of Figure 1
"The red curves in the top left panels in (a) and (b) compare the diurnal mean TEC with the first basis vector U1 and the solar radio flux index measured at 10.7 cm wavelength (F10.7) with coefficients C1 of the first EOF mode respectively"

Comment 4: (Page 4, line 16) A period of 0 means a harmonic function of infinite angular frequency. The statement is incorrect.

Response: It is true that the statement is incorrect. This was changed in page 5 lines 16-17 to: We then expressed the EOF coefficients as a sum of linear and harmonic functions following the procedure of Zhang et al. (2009) as

Comment 5: (Page 4, Table 1) Please specify that the explained variances and cumulative variances are expressed in percentage.

Response: Percentage sign (%) has been added in Table 1

Comment 6: (Page 5, lines 3 - 5) The sentence is wrong. The least square method is used to estimate EOF coefficients from the exact coefficients C j (and not GPS-derived TEC as mentioned) and model inputs. (Please see Equation 5).

Response: Thank you for the observation. The sentence was corrected to:
The coefficients a_{j1} to f_{j3} in equations 5-7 were determined using a least squares fit to the EOF coefficients $C_j(d)$ in equation 3 obtained from GPS-derived TEC values measured at Malindi. The above sentence is in page 6 lines 7-8

Comment 7: Specify the inputs of the models in section 2.

Response: We added the sentence below to specify the inputs to the model:
"Based on the observations in Table 2, it was reasonable to use F10.7av and Dst as inputs to model the solar and magnetic dependences of TEC over Malindi. Since Dst and F10.7av vary with the day of the year (DOY), our third input parameter was the DOY number". This appears in page 5 lines 14-16

Comment 8: (Page 7) Comment about the failure/inaccuracy of IRI in predicting TEC during storms. IRI and GPS satellites provide TEC up to 2000 km and 20,200 km altitude, respectively. Comment discuss about this and the plasmaspheric contributions.

Response: Thank you for the suggestions. It is expected that the altitude difference would result in lower IRI TEC than GPS TEC due to the plasmaspheric contribution to the GPS TEC. However some observations (eg. Olwendo *et al.* 2012) over the East African region show that IRI overestimates the GPS TEC during low solar activity years and during June solstice. Such a difference may not be accounted for in terms of the altitude

Like any other empirical model, the IRI is limited. The inaccuracy of IRI in predicting TEC during storms over Malindi probably leaves an open research question. There may be need to improve on the storm model used in IRI in order to capture the different storm time TEC responses. A similar comment has been made in page 7 lines 23-25.

Comment 10: (Page 6, Figure 3): Add Kp index as the authors have used it to select quiet days.

Response: The maximum Kp and the minimum Dst for each of the days has been included in the plots in Figure 3

Comment 11: (Page 7, Figure 4): Specify in the text that top panels represents Dst index.

Response: The following sentence was added in the text in page 7 lines 29-30:
"The bottom panels of Figure 4 show variation of the hourly diurnal TEC while the top panels show variation of Dst index during some selected major geomagnetic storms"

References

Jee G., Lee H. B., Kim Y. H., Chung J. K. and Cho J., 2010. Assessment of GPS global ionosphere maps (GIM) by comparison between CODE GIM and TOPEX/Jason TEC data: Ionospheric perspective. J. Geophys. Res.: space physics,115, p A10319

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Hannachi A., Jolliffe I.T. and Stephenson D.B., 2007. Empirical orthogonal functions and related techniques in atmospheric science: A review. Int. J. Climatol., 27, pp. 1119–1152.

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