Response to Reviewer#RC1

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

Response
Thank you for the inquiry. Singular Value Decomposition factorizes a matrix $M_{m\times n}$ in to 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. Therefore there is no mean term in Equation 1

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 maxima 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 3:00 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.

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 curve in (a) and (b) show the diurnal variation of average TEC from 1999-2017 over MAL2 and the daily solar radio flux measured at 10.7 cm wavelength (F10.7) 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 as follows.

For an effective TEC model, the choice of parameters to model the solar and magnetic activity influences on the TEC is important. Based on our observations in Table RC1, it was reasonable to use F10.7av and Dst indices to model the solar and magnetic dependences of TEC over Malindi. We then expressed the EOF coefficients as a sum of linear and harmonic functions following the procedure of Zhang *et al.* (2009) as

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

The linear 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

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

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 0.5 and 1 year (365.25 days) respectively as

$$\mathrm{B_{j2}(d) = \left[a_{j2} + b_{j2}F10.7_{av}(d) + c_{j2}Dst(d)\right] \cos\left(\frac{2\pi d}{365.25}\right) + \left[d_{j2} + e_{j2}F10.7_{av}(d) + f_{j2}Dst(d)\right] \sin\left(\frac{2\pi d}{365.25}\right)} \quad (1)$$

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

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

Response
We have provided a reference 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.

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

	Solar indices			Magnetic indices		
	SSN	F10.7	F10.7$_{\text{av}}$	Kp	AE	Dst
C1	71.2(**71.6**)	75.8(**76.0**)	79.1(**79.2**)	19.0(18.8)	15.6(15.1)	-23.1(-23.0)
C2	36.6(**37.0**)	35.4(35.2)	37.2(37.1)	9.5(8.7)	12.1(10.0)	-5.5(**-6.0**)
C3	16.9(**17.4**)	16.7(**17.2**)	16.4(**16.7**)	4.2(**7.2**)	4.6(**9.1**)	-4.1(-1.6)
C4	4.4(**4.8**)	7.5(**8.0**)	8.1(**8.5**)	17.8(14.4)	20.1(18.4)	-13.3(-4.0)
C5	5.8(**5.9**)	6.9(6.9)	7.0(7.0)	2.3(0.3)	1.3(0.2)	-6.8(-6.5)
C6	0.2(0.2)	1.9(1.6)	1.8(1.6)	1.8(0.7)	3.9(1.8)	-4.4(-3.1)

(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 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 (eg 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 Latovicka 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

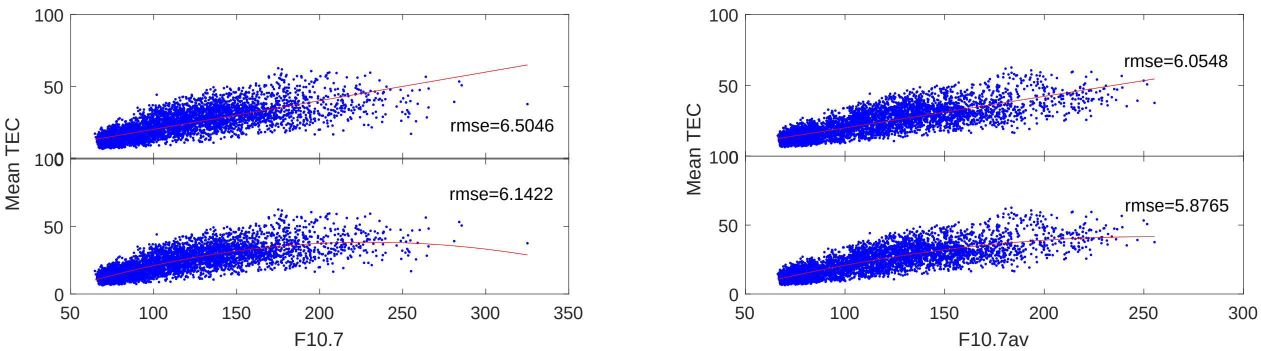
Thank you for the suggestions. Appropriate references were cited as suggested

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.

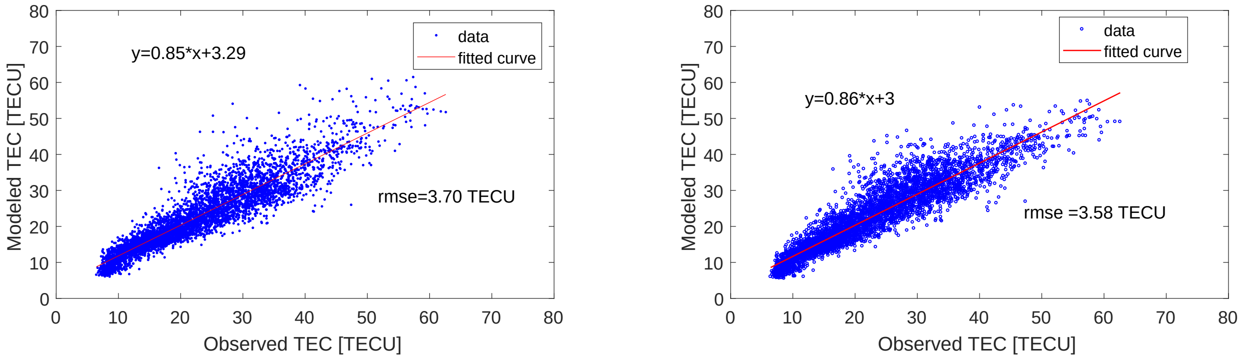
$$\mathrm{C_j(d) = B_{j1}(d) + B_{j2}(d) + B_{j3}(d)}$$

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

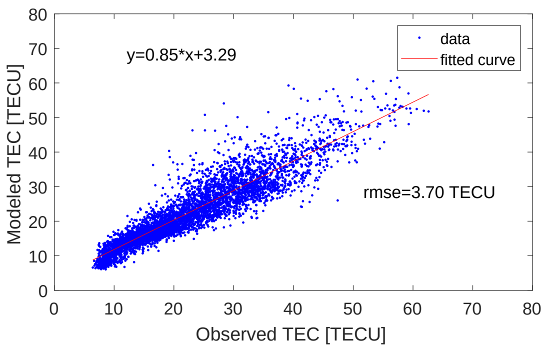


Figure RC3: Correlation between the daily averages of the modeled TEC and GPS TEC over MAL2.

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 curved solid white line shows the geomagnetic dip equator, and the curved dashed white lines show $\pm 15°$ 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. The possible influence could be from 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 these are shown in Figure RC4 and Figure RC5. This clearly shows that the trend does vary with the local time. The diurnal pattern obtained from the different data sources is essentially the same (Figure RC4). The latitudinal variation in the trends appear to be more prominent from 21:00-24:00 LT. The diurnal variation in the trends will be included in the revised manuscript

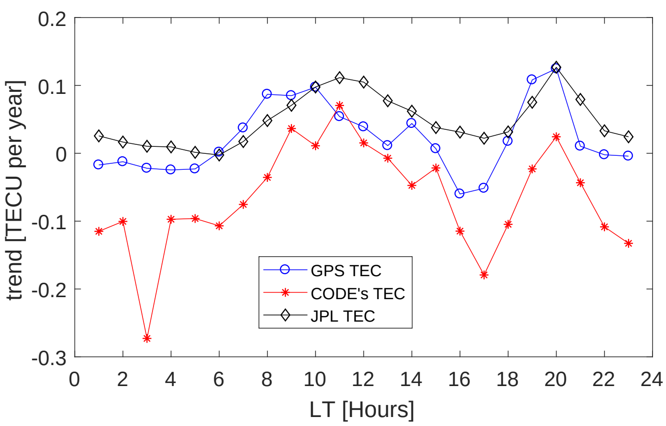


Figure RC4: Diurnal variation of TEC trends over MAL2 in the period 2003-2017

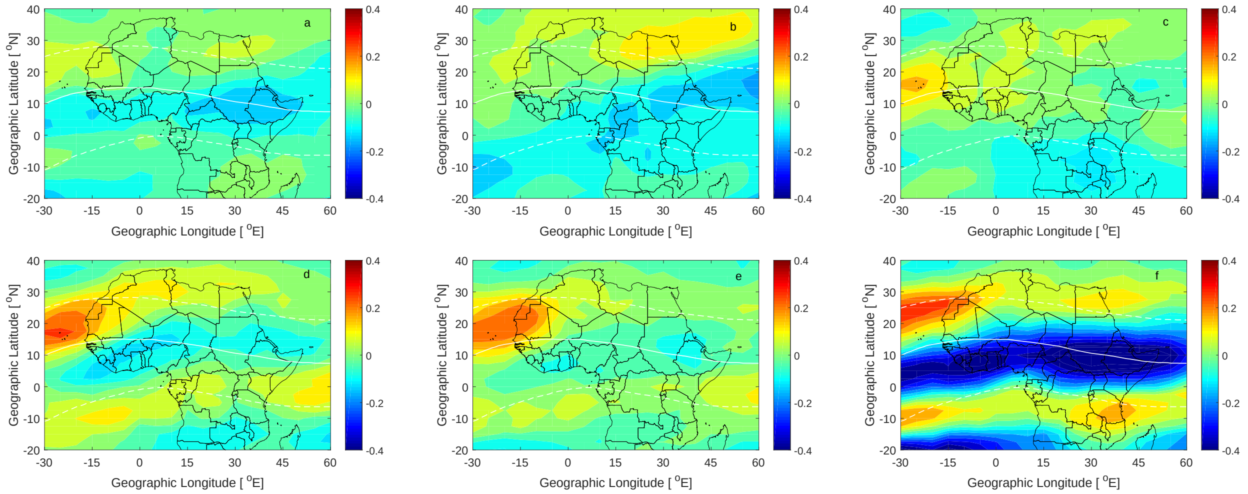


Figure RC5: Local time variation of TEC trends for the period 2003-2017. The trends shown were obtained by averaging the TEC from (a) 1:00-4:00, (b) 5:00-8:00, (c) 9:00-12:00, (d) 13:00-16:00, (e) 17:00-20:00 and (f) 21:00-24:00 LT.

References

Bremer J., Damboldt T., Mielich J. and Suessmann P., 2012. Comparing long-term trends in the ionospheric F2-region with two different methods. J. Atmos. Sol.-Terr., 77, pp. 174–185.

Ercha A., Zhang D., Ridley A.J., Xiao Z. and Hao Y., 2012. A global model: Empirical orthogonal function analysis of total electron content 1999–2009 data. J. Geophys. Res., 117, p. A03328.

Lastovicka J., 2013. Are trends in total electron content (TEC) really positive. J. Geophys. Res.: space physics,118, pp. 3831–3835.

Lastovicka J., Urbar J. and Kozubek M., 2017. Long-term trends in the total electron content. Geophys. Res. Let., 44, p. 8168–8172.

Lean J.L., Emmert J.T., Picone J.M. and Meier R.R., 2011. Global and regional trends in ionospheric total electron content. J. Geophys. Res., 116, p. A00H04.

Ogawa Y., Motoba T., Buchert S. C., Haggstrom I. and Nozawa S., 2014,. Upper atmosphere cooling over the past 33 years. J. Geophys. Res. Lett., 41, pp. 5629–5635

Richards P. G., Fennelly J. A., Torr D. G., 1994. EUVAC:A solar EUV flux model for aeronomic calculations. J. Geophys. Res., 99, pp. 8981–8992.

Scherliess .L and Fejer B G.,1997. Storm time dependence of equatorial disturbance dynamo zonal electric fields. J. Geophys. Res., 102, pp. 24037–24046.

Uwamahoro, J. C., and Habarulema J. B., 2015. Modelling total electron content during geomagnetic storm conditions using empirical orthogonal functions and neural networks. J. Geophys. Res. Space Physics, 120, pp. 11000–11012.

Zhang M.L., Liu C., Wan W., Liu L. and Ning B., 2009. A global model of the ionospheric F2 peak height based on EOF analysis. Ann.Geophys., 27, pp. 3203–3212.