Reply to second Reviewer's Comments:

Interactive comment on "Long-term trends in the ionospheric response to solar EUV variations" by Rajesh Vaishnav et al.

Anonymous Referee #2

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The manuscript presents a new and very interesting study of the ionospheric response to solar activity. Solar activity is represented by individual solar proxy datasets. The authors study the correlation and lag of the variability of solar proxies with the response in the ionosphere/thermosphere, represented by the total electron. Of key interest is which solar activity proxies best describe the ionospheric response. In their study the authors employ a principal component analysis, empirical orthogonal functions (EOFs) as well as the cross-wavelet analysis and Lomb Scargle periodogram (LSP).

Response: The authors are thankful to the reviewer for the critical comments and encouraging suggestions, which helped to improve the quality of the manuscript. We will address all the raised points in the revised version of the manuscript.

Major Comments: ==========

The authors present new and also very interesting results. However, additional clarifications are still to recommend the paper for publication. The result of the lag is presented in the text mainly as lag of one or two days. As the result of the lag is also an important result it needs to be presented more precisely, i.e. with at least one (or better two) digits after the comma, i.e. 1.8 (e.g. from Figure 8), corresponding to maximum of the cc-curve?

Response: The authors are thankful to the reviewer for appreciating our findings. In this analysis, we have used all the datasets (GTEC and Solar proxies) at a daily resolution, as our used solar proxies are available in daily resolution. So, the calculated delay will be in the day(s) only. We will mark the maximum of cc curves in Fig. 8, where the delay is 1 or 2 days.

In the abstract (Line 26ff) the authors state that "Empirical orthogonal function (EOF) analysis of the TEC data shows that the first EOF components capture more than 86% of the variance, and the first three EOF components explain 99% of the total variance." The authors should specify who the contributions (86%,

ect) are determined. The authors state that the first EOF is the solar component. Could the authors elaborate on the other EOFs under consideration (in particular the 2nd and 3rd). This is partly done in lines 192ff. Could the dynamics of the Earth's atmosphere also play a role?

Response: In the revised version, we will add a brief description of EOF analysis in section 3.6, including the calculation of explained variance, and also we will update the abstract. Actually EOF1 includes the solar variability effect, as it is symmetric about the equator. This includes Earth's eccentricity effect also.
EOF2 is antisymmetric about the equator, with the maximum during the winter (see PC2). This indicated that EOF2 includes the seasonal effect, including dynamical effects in the ionosphere.
PC3 is correlated with magnetic activity (See Fig. 13) so we attribute EOF3 with magnetic effects. PC4 shows a slight trend. One may speculate that this might be due to secular changes of the magnetic equator.

The link between the EOFs and PCs is not clear. In Figure 11 the authors plot EOF1 to EOF4. In Figure 12 and 14 the authors show the CC of the PCs with proxies, and in Lines 302 the authors state "In order to check the relation between solar proxies and geomagnetic parameters (daily Kp, Dst, and Ap indices) with PCs corresponding to EOFs, cross-correlation and delay is calculated and shown in Figure 12." Could the authors elaborate better how the EOFs and PCs are derived and what is the time series for the CC in Figs 12 and 14.

Response: We will discuss the link between EOFs and PCs with the formula in section 3.6. To calculate the maximum CC in Figs 12 (new figure, 13) and Fig. 14 (new figure, 15), we have used time series of PCs and different parameters including solar and geomagnetic parameters from the 1 January 1999 to 31 December 2017.

In the introduction, further references to previous work should be mentioned e.g.: http://adsabs.harvard.edu/abs/2016JGRA..12110367L and others.

Response: We will add more references in the revised version.

For the determination of the lag is not clear. How is it derived. Possibly it should be the lag value for the maximum correlation. Please give precise values for the lag (e.g. 1.8 in Figure 8.)

Response: We have derived the lag as the value for the maximum correlation. We have used daily resolution datasets as all the used solar proxies are available in daily resolution. So, the calculated delay will be in the day(s) only.

Minor comments: ==========

Line 2: please clarify or rephrase "spatial dynamic of solar activity". The solar proxies under consideration do contain any spatial information, possibly the authors mean "the spatial response of the ionosphere to solar activity"?
Response: We will rephrase this sentence as suggested.

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Line 10: GNSS, explain acronym when first mentioned
Response: We will add the acronym.

Line 35ff: "These studies have shown, that the response of the ionosphere to solar EUV radiation variations takes 1-2 days for solar radiation changes within 27 days solar rotation period". This sentence is not clear, could the authors please rewrite it.
Response: We apologize for this error. We will correct this in the revised manuscript: “These studies have shown that the response of the ionosphere to solar EUV radiation variations gets delayed by 1-2 days at 27 days solar rotation period”

Line 13: A 16-32 days period -> A 16 to 32-day period (day, without s)
Response: We will improve this as suggested by the reviewer in the revised version.

Line 15: LSP analysis -> The LSP analysis
Response: We will improve this as suggested by the reviewer in the revised version.

Line 18: "The wavelet variance estimation method is used to find the variance in the maximum of the solar cycles (SC) 23 (2000-2002) and 24 (2012-2014), for GTEC and F10.7 index, respectively. " Suggested rephrasing, as the sentence does not read very well. -> The wavelet variance estimation method is used to find the variance of GTEC and F10.7 over the maxima of the solar cycles SC 23 and SC 24. The selected time frame that covers the solar maxima are .... and ....
Response: We will rephrase this sentence as suggested.

Line 20: GTEC variance -> the GTEC variance
Response: We will improve this as suggested by the reviewer in the revised version.

Line 20: seasonal timescale: which one is considered as the seasonal time scale? 32-64-day period? please specify or rather give the name of the wavelet window. Generally, the wavelet intervals could be numbered so that the interval does not need to be repeated in the text again.

Response: Yes, the 32 to 64-day period is considered as seasonal timescale. We will add this in the revised version of the manuscript.

Line 22: to represent the solar activity -> to represent solar activity

Response: We will improve this in the revised text.

Line 23: may be placed at the second ... -> may be placed second ...

Response: We will improve this in the revised text.

Line 24: but there are some differences between solar maximum and minimum: could the authors be more specific.

Response: We will rephrase the sentence in the revised version of the manuscript.

Line 25: The F1.8 and DSA ... -> The indices F1.8 and DSA ...

Response: We will improve this in the revised text.

Line 26: Empirical orthogonal function (EOF) analysis -> The Empirical orthogonal function (EOF)

Response: We will improve this in the revised text.

Line 27: "EOF analysis suggests that the first component is associated with the solar flux." This result is expected, but also very nice to be an outcome of the EOF analysis. Could the authors also indicate what the status of the knowledge/hypothesis about the nature of the subsequent 2-3 EOF components are (dynamics, ect).

Response: Thanks for the suggestion. We will add it in the abstract.

Line 33: reference Chen et al., 2012: Please add more references.

Response: We will add more references in the revised version.

Line 36 (and elsewhere in the manuscript): These studies have shown, that the response of the ionosphere to solar EUV radiation variations takes 1-2 days.: A quantitative analysis of the response time of the ionosphere to the EUV radiation is an important result. As already stated above, this needs to be presented in a more quantitative and presice way. Could the authors also give the precise values for the lag for all studies undertaken, e.g. in a table, or in.

Response: We completely agree with the reviewer's suggestion but the delay is still not analysed in high resolution due to unavailability of high-resolution datasets of solar EUV proxies. Schmölter et al. 2018 analysed SDO EVE and TEC datasets at hourly resolution and they reported a delay of about 17 hours. Hence due to unavailability of long-term high resolution solar EUV observations, in this paper, we have used daily datasets. Most of the researcher reported the delay about 1-2 days just because of the unavailability of hourly solar proxies.

Line 43: Investigate ... mechanism -> investigate the ... mechanism
Response: We will improve this in the revised text.

Line 48: "The T-I system is also influenced by different external forces": the solar forcing should also be considered as "external forcing". Therefore, aren't all forcings "external"?
Response: We agree with your concern. We will improve this in the revised manuscript.

Line 49: "In the case of solar events, the forcing from above might even result in strong disturbances affecting the ionospheric delay." -> This sentence needs to be revised. Suggestion: In addition to the solar EUV forcing, the solar wind as well as solar eruptions might also result in ... Could the authors give references that address this work?
Response: We will add references and rephrase the sentence as suggested.

Line 50: "As a result, the ionospheric plasma behaviour is varying during different solar activity conditions." It is not clear what is meant here. Please revise this sentence.
Response: We will revise it.

Line 51-58 (full paragraph): The authors mention the 27-day solar rotation period and its effects on the TEC. What is missing in Hocke (2008). Why are further investigations needed?
Response: We apologize for the typo error. We will correct this in the revised version.

Line 57ff: "Many studies ...". Sentence seems out of place here, move above as the paragraph above seems to be the introduction to the 27-day variability. Also please give some references to the "many studies".
Response: We will merge this sentence as per reviewer suggestions and include references.

Line 59: Since direct EUV measurements ... and are still not available in the full spectrum...: In recent times the situation of the EUV measurements has considerably improved (thanks to e.g. SDO/EVE, see also http://lasp.colorado.edu/lisird/). Also, while degradation of space instruments is still a challenge, the availability of SSI data in the EUV (either direct measurements, composite datasets or models) has improved, see e.g. Lean et al. http://adsabs.harvard.edu/abs/2003JGRA..108.1059L Haberreiter et al., 2017, composite covers the full spectrum, incl. the EUV Please revisit the statement.
Response: We agree with the reviewer's suggestions. It will be improved in the revised version of the manuscript.

Line 63: .. and indices based on direct EUV measurements (e.g., Unglaub et al., 2011) like the Solar EUV Experiment (SEE) onboard the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite (Woods et al., 2000). -> .. and indices developed by Unglaub et al. (2011) based on direct EUV measurements obtained with the Solar EUV Experiment (SEE) onboard the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite (Woods et al., 2000).
Response: We will replace this sentence as suggested.

Line 65: which may be overcome by repeated calibration -> please clarify what is meant here, inflight calibration is repeated calibration. Do the authors mean rocket calibrations of flight spares as done with SDO/EVE?
Response: Yes, repeated calibration of EUV spectrometers.

Line 93: OMNIWeb Plus database: please give a reference and/or link to the database.
Response: We will add the link and reference as suggested.

Line 103: The zonal mean plot additional temporal variations: please explain which those are.
Response: We will rephrase the sentence with clarification.

Line 105: around the magnetic equator: the variation seems rather symmetric around the equator. The magnetic equator should possibly be indicated in the plot if possible, or would "the equator" be sufficient.
Response: Thanks for the suggestion. We will add the magnetic equator line in the plot.

Line 107: is varies -> varies
Response: We will improve this in the revised text.

Line 109: delete "E.g." at the beginning of the sentence
Response: We will improve this in the revised text.

Line 110: "As all the time series in Figure 1 show a similar overall variation during the 11-year solar cycle, the fundamental behaviour of solar radiation emission is identical at all the wavelengths." A lot of care needs to be taken here. Actually, the fundamental behaviour is not the same for all wavelength, as the plasma heating and atomic processes are different for different wavelength. Specifically, for the radio proxies the processes for the various proxies are

different (see Dudok de Wit, et al., 2014, http://adsabs.harvard.edu/abs/2014JSWSC...4A..06D)
Response: We agree with the reviewer's suggestion. We will rephrase the sentence.

Line 120: Note that the T-I system is not only influenced by solar activity but also by changing geomagnetic conditions due to solar wind variations. -> Please revise, suggestion: Note that the T-I system is not only influenced by the solar electromagnetic radiation but also by changing solar energetic particles and geomagnetic conditions due to solar wind variations or Coronal Mass Ejections reaching the Earth. Please also give reference to support this. Effect of particles on the Earth upper atmosphere?
Response: We will replace this sentence as suggested by the reviewer. We will discuss the effect of particles on the upper atmosphere. Actually, the Sun's energetic particles deposition to the Earth's atmosphere is very complicated, and its interaction with the magnetic field plays an important role since the charged particles are guided along magnetic field lines. Thus low latitudes are shielded from much but not all of the incoming charged particles with most of the energetic particles being guided into the Earth's atmosphere in the polar regions. Hence these particles majorly influence the polar regions.

Line 121: Strong solar activity during solar maxima might induce stronger interaction...: Please revise sentence, suggestion: The response to solar forcing is higher during solar maximum... Please also add references. The solar wind, in particular from coronal holes, also occurs during solar minimum conditions. Please take this also into account.
Response: Thanks for the suggestion. We will revise it in the revised version of the manuscript.

Line 135: This allows to determine dominant joint oscillations -> This allows us to determine dominant correlated oscillations (or other word for "joint")
Response: We will replace this sentence as suggested by the reviewer.

Line 137: 16-32 days period region -> 16 to 32-day interval (also elsewhere in the text)
Response: We will improve this throughout the manuscript in the revised version as suggested by the reviewer.

Line 138: the ionospheric variation due to the solar activity is lower -> the ionospheric variation is lower due to solar activity
Response: We will replace this sentence as suggested by the reviewer.

Line 142: The black arrows in Figure 3 indicate the phase relationship between solar proxies and GTEC (also caption of Figure 3): What does the upward orientation of the arrow mean?
Response: We will add the description of arrows in the revised version of the manuscript.

Line 144: the annual and semi-annual period range -> ranges? Could you give the exact interval for those. It is two separate intervals that are meant here? Please clarify.
Response: Yes, these are two separate intervals: the annual (256 to 512-day) and semi-annual (128 to 256 day). We will add it in the revised version of the manuscript.

Line 153: ... semi-annual. The observed periodicities in GTEC are also shown by Hocke (2008). -> ... semi-annual, which is in line with Hocke (2008) (if this is what is meant).
Response: Yes, we will rephrase the sentence as per suggestion.

Line 154: It is interesting to note here that a 44-day periodicity is observed in GTEC and all other solar proxies.: From Figure 4 the 44-day variability seems not significant. It seems that there is random variability in the window up to 1/2 year. Of the same order of magnitude in the time series. Without further analysis it cannot be stated that a 44-day variability is visible in "all other solar proxies". Please revise.
Response: We agree with the reviewer suggestion. We will include 95% confidence line in the updated Figure. 45 days periodicity is observed in F10.7, Mg II and SSN. Hence, we will revise the statement as per suggestions.

Line 156: .. and it's 2nd harmonic 13.5 days, and 4th harmonic 6.7 days...: Please also indicate these harmonics in Figure 17.
Response: Thanks for the suggestion. We will update the figure as suggested.

Line 157: Here similar kind of oscillations..: Do the authors find the same oscillations, i.e. 2nd harmonic 13.5 days, and 4th harmonic 6.7 days. Or are they different for Lyman alpha. If so, please specify.
Response: We will revise the text. Both Mg II and Ly-alpha shows the same periodicity.

Line 157: Ly-$nalpha$ - Ly-$nalpha$ (take out space)
Response: We will improve it in the revised version.

Line 159ff: Note that the wavelet spectra show some periodicity at the half-year time scale, but with variable phase so that they extinguish in the periodogram.:

This sentence needs to be revisited. For which proxies? In Figure 4 only the GTEC and and maybe F30 show a 1/2 year peak. Please be specific.
Response: We will add specific proxies and revise the sentence.

Line 162: Maybe add a subtitle here: "Wavelet Cross-Correlation"
Response: We will add the title as suggested by the reviewer.

Line 164: using ->based on (repetition from line 163)
Response: We will replace this word in the revised version of the manuscript.

Line 167: The delay is mostly positive or zero, which means that TEC is following the solar proxies with delay. -> The delay is mostly positive or zero, which means that TEC is following the solar proxies.
Response: We will replace this sentence in the revised version of the manuscript.

Line 170: ... by about one day: could you please give the exact value here (and everywhere in the text when the lag is given)? E.g. Line 176, 176
Response: As mentioned above, in this analysis we have used all the datasets (GTEC and Solar proxies) at the daily resolution, as solar proxies are available in daily resolution. So, the calculated delay will be in the day(s) only.

Line 184: A stronger correlation -> A strong correlation
Response: We will replace this in the revised version of the manuscript.

Line 186: for the GTEC -> for GTEC
Response: We will improve this in the revised text.

Line 186: with Daubechies 2 ... -> with the Daubechies
Response: We will improve this in the revised text.

Line 194: There is no strong semi-annual cycle visible. -> ... and as expected, no significant semi-annual cycle is visible.
Response: We will improve this in the revised text.

Line 199: inter-annual time scales: these are timescales of one year or larger? Please clarify. Maybe "time scales below (or above) one year"
Response: Yes, we have considered all the variability below and above one year. We will add this in the revised version.

Line 200: 365 days running window -> 365-day running winding
Response: We will improve this in the revised text.

Line 203: All solar proxies show similar behaviour during low activity conditions: While the temporal variation of the CC for Mg II, Ly alpha and He II is largely similar, the SSN (green curve) shows a significantly different behaviour.
Response: We will revise it.

Line 203: apart from a different mean level: Not sure what the author mean as "mean level". It could be stated that SSN generally shows a lower CC than the other proxies.
Response: We apologize for this error. We will rephrase the text as per reviewers suggestions.

Line 208: Are the cross-correlations shown in Fig. 8 a temporal mean over the years 199 to 2017. It would be very interesting to see the temporal variation, e.g. similar to Fig. 7, if possible.
Response: No, this is maximum cross-correlation calculated at 27 days solar rotation period. We will add a description in the revised version of the manuscript. Thanks for the suggestion, we will add the temporal variation plots for GTEC, low latitude, mid-latitude, and high latitude TEC in the appendix.

Line 210ff: "As in Figure 7, the correlation of F10.7 with TEC is weaker than the one of MG-II and TEC.". However, F10.7 is not shown in Fig. 7. Please revise.
Response: We apologize for this error. We will revise it in the revised version.

Line 210ff (disucussion of Fig. 8). Maybe start out with: Generally, the correlation coefficient and the lag for the Global, NH, SH, LL, and ML are very close. Then continue: The maximum correlation is found... The weakest correlation is observed...
Response: We will improve this in the revised text.

Line 211: HL with maximum correlation coefficients -> HL with a maximum correlation coefficient of
Response: We will improve this in the revised text.

Line 215: "response time of about two and one days": As already mentioned above, could the authors give a more precise result for the lag, i.e. derived from the maximum of the curves in Fig. 8. It might be something like 1.8 or 1.9. Please also mark the maximum of each curves in Fig. 8 with a cross or similar.
Response: We will mark the maximum of each curve with a cross.

Line 225: is shown -> is found
Response: We will improve this in the revised text.

Line235: From the above discussion it is clear that during -> In summary, during low solar activity... ; please also add a summary sentence for high solar activity
Response: We will improve this in the revised text.

Line 238: indices shows stronger -> indices show a stronger
Response: We will improve this in the revised text.

Line 239: of about 1-3 days: again, please provide a more precise determinination of the lag.
Response: As mentioned above, in this analysis we have used all the datasets (GTEC and Solar proxies) at the daily resolution, as solar proxies are available in daily resolution. So, the calculated delay will be in the day(s) only.

274: using Empirical Orthogonal Function (EOF) which decomposes -> Empirical Orthogonal Functions (EOFs), which decompose
Response: We will improve this in the revised text.

Line 276: to represents -> to represent
Response: We will improve this in the revised text.

Line 282: How do the authors derive the contributions of the PC1, PC2, ect of about 86%, 11%, ect. Please add this to the text.
The result of EOF2, 11%, is given in brackets in line 282 and 292 again. The first mention could be removed, as the text is then better to read.
Response: We will add the description of PC extraction and rephrase the paragraph as per the reviewer suggestion in the revised version of the manuscript.

Line 299: remove "only", as both semi-annual and annual oscillations are visible.
Response: We will remove this word.

Lien 302: In order to check the relation between solar proxies and geomagnetic parameters (daily Kp, Dst, and Ap indices) with PCs corresponding to EOFs, cross-correlation and delay is calculated and shown in Figure 12. The color-coded value in Fig. 12 is the temporal average of the correlation coefficient? This should be stated in the text and the figure caption. Figure 12 (and Figure 14) are very interesting result of the paper. Therefore, it would be very interesting to also see the temporal variability of the correlation (also similar to Fig. 7 for the solar proxies). Could the authors provide this for completeness (at least for a few cases), possibly in the appendix?
Response: We will add temporal variability plots for all four PCs for Figure 12 in the appendix.

Line 315: is capturing -> captures

Response: We will improve this in the revised text.

Figures: Figures in general: a number of panels are rather on the small side. It is recommended to fill the full text width in order to make the figures better readable Figure 1, 3, 8, 10, 11 : enlarge panels to 0.5 textwidth
Response: Thanks for the suggestions. We will improve all the Figures as per the reviewer suggestions.

Figure 11: Panels need to be enlarged, as it is difficult to see the details in the printed version of the manuscript. The panels should be of the size of the new Fig. 10, i.e. only two panels next to each other. Could Figure 11 be split, say PC1 and PC2 in one figure, and PC3/PC4 in another?
Response: Thanks for the suggestions. We will split Figure 11 into two Figures as suggested by the reviewer.

Caption Figure 8: please add: Temporal mean (cross correlation .... during the years 1999 to 2017) for different lags.
Response: We will improve the caption.

Caption Figure 9: The background colors show the correlation coefficient -> The background colors give the temporal mean of the correlation coefficient (or maximum?), please clarify which cc is shown throughout the text.
Response: Thanks for the suggestions. We will improve the Figures and captions as per the reviewer suggestions.

Throughout the text: He-II-> He II (no hyphen) MG-II-> Mg II (no hyphen) CaK -> Ca II K 16-32 days period -> 16 to 32-day period (day always without s) thoughout the text and figure captions The authors often show a correlation coefficient (Figure 8, Figs 12, 14, ect). Please specify if it is a temporal mean, spatial mean, maximum value corresponding to a lag value? Use Figure xx (at the beginning of the sentence, as in Line 106) and its abbreviation Fig. xx (in sentence, as e.g. in line 105) consistently throughout the text. Generally, the second part of the paper, starting with lines 208 reads more fluent. Could the (co-)authors go over the manuscript for language and typos.
Response: Thanks for the suggestions. We will improve the text as per the reviewer suggestions.