

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).

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

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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?

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?

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.

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

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.)

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"? Line 10: GNSS, explain acronym when first mentioned Line 35ff: "These studies have shown, that the response of the ionosphere to solar EUV radiation vari-

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ations 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.

Line 13: A 16-32 days period -> A 16 to 32-day period (day, without s) Line 15: LSP analysis -> The LSP analysis 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

Line 20: GTEC variance -> the GTEC variance 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 intervall does not need to be repeated in the text again.

Line 22: to represent the solar activity -> to represent solar activity Line 23: may be placed at the second ... -> may be placed second ... Line 24: but there are some differences between solar maximum and minimum: could the authors be more specific. Line 25: The F1.8 and DSA ... -> The indices F1.8 and DSA ... Line 26: Empirical orthogonal function (EOF) analysis -> The Empirical orthogonal function (EOF)

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

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authors also give the precise values for the lag for all studies undertaken, e.g. in a table, or in . Line 43: investigate ... mechanism -> investigate the ... mechanism 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"? 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? 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. 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? 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". 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. 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). Line 65: which may be overcome by repeated calibration -> please clarify what is meant here,

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inflight calibration is repeated calibration. Do the authors mean rocket calibrations of flight spares as done with SDO/EVE? Line 93: OMNIWeb Plus database: please give a reference and/or link to the database. Line 103: The zonal mean plot additional temporal variations: please explain which those are. 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. Line 107: is varies -> varies Line 109: delete "E.g." at the beginning of the sentence 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>) 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? 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. Line 135: This allows to determine dominant joint oscillations -> This allows us to determine dominant correlated oscillations (or other word for "joint") Line 137: 16-32 days period region -> 16 to 32-day interval (also elsewhere in the text) Line 138: the ionospheric variation due to the solar activity is lower -> the ionospheric variation is lower due to solar activity Line 142: The black arrows in Figure 3 indicate the phase relationship between solar proxies

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and GTEC (also caption of Figure 3): What does the upward orientation of the arrow mean? 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. 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). 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. Line 156: .. and it's 2nd harmonic 13.5 days, and 4th harmonic 6.7 days...: Please also indicate these harmonics in Figure 17. 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. Line 157: Ly- α - Ly- α (take out space) 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. Line 162: Maybe add a subtitle here: "Wavelet Cross-Correlation" Line 164: using -> based on (repetition from line 163) 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. 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 Line 184: A stronger correlation -> A strong correlation Line 186: for the GTEC -> for GTEC Line 186: with Daubechies 2 ... -> with the Daubechies Line 194: There is no strong semi-annual cycle visible. -> ... and as expected, no significant semi-annual cycle is visible. Line 199: inter-annual time scales: these are timescales of one year or larger? Please clarify. Maybe "time scales below (or above) one year" Line 200: 365 days running window -> 365-day running winding

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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. 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. 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. 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. Line 210ff (discussion 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... Line 211: HL with maximum correlation coefficients -> HL with a maximum correlation coefficient of 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. Line 225: is shown -> is found Line 235: 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 Line 238: indices shows stronger -> indices show a stronger Line 239: of about 1-3 days: again, please provide a more precise determination of the lag. 274: using Empirical Orthogonal Function (EOF) which decomposes -> Empirical Orthogonal Functions (EOFs), which decompose Line 276: to represents -> to represent 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. Line 299: remove "only", as both semi-annual and annual oscillations are visible. Line 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 calcu-

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lated 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? Line 315: is capturing -> captures

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
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?
Caption Figure 8: please add: Temporal mean (cross correlation during the years 1999 to 2017) for different lags.
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.

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) throughout 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.

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