We revised our manuscript according to the received advice. Thank you for the detailed comments and suggestions in the reviews!

RC1:

1. In Figure 3, the authors compared the correlation coefficients and the time delay retrieved from two datasets by fixing local time or fixing location. The authors should note that the time delay of ionosphere to the solar EUV flux change depends on solar local time. The time delay inferred from fixed location dataset can be partly considered as the averaged delay at different local times. The authors should point out this issue.

Answer: We clarified the difference between local time and fixed location analysis as suggested.

Line 130: “The delayed ionospheric response to solar EUV radiation depends on the solar local time and the calculated results for fixed locations can be understood as a mean ionospheric delay for different local times. The local time approach would be preferred for this reason.”

2. The time delay of ionospheric parameters is the key in this analysis. The difference between the time delay by using the 2 methods is greater than 4 hours. How about the uncertainty of the obtained time delay? In addition, the diurnal variation of ionospheric parameters may affect the calculation of time delay. They can provide the time delay by removing the diurnal variation in Figure 3.

Answer: We added an explanation of the mean difference (approximately 3.15 hours) between both approaches and characterized the uncertainty.

Line 126: “The two different approaches have a mean variance of approximately 3.15 hours, which accounts for an uncertainty of approximately 16.04 % in the ionospheric delay calculation. This is an acceptable impact of the diurnal variation on the trend of the delay for characterizing temporal and spatial changes.”

The time delay can be provided without the diurnal variation, but the available approaches don’t improve the process or even have a negative impact. Removing the diurnal variation with a band-stop filter doesn’t remove the diurnal variation completely and there is no improvement for the correlation and reliability of the delay (Schmölter et al., 2018). Calculating daily mean values for TEC or foF2 doesn’t allow a delay analysis on hourly resolution, since that would require interpolation back to the high resolution and this in turn has a huge impact on the delay calculation. In general, an improvement of the correlation coefficients (e.g. calculating daily means) doesn’t grant a more reliable or precise delay calculation. We decided against filters or changes on the signal, acknowledge the impact of the diurnal variation and focus on features of the ionospheric delay, which are not defined by small scale changes. In addition, the calculated value range and features of the delay trend fit very well with results of preceding studies.

3. Is the time delay reliable as the correlation coefficient is less than 0.4?

Answer: The results are statistically significant due to the big sample size (90 days on hourly resolution) and, as shown by Figures 2 and 3, the relative trend of correlation coefficients and delay is not changed in different approaches. For example using fixed local times gives much higher correlation coefficients and the resulting annual variation of the delay is present.

We clarified the reliability in the manuscript as mentioned in the reply to comment 2.

4. How do they calculate the Kp index, the red line in Figure 4?

Answer: We clarified the description of Figure 4. The Kp-index data are shown in weekly resolution with the red line, because the trend on hourly or daily resolution doesn't give a meaningful overview for the long-term changes due to the much stronger short-term variations. A description for the calculation of the smoothed trends is added as well.

Figure 4: "The transparent red lines or dots show the raw data: Kp-index in weekly resolution (a), correlation coefficients between EUV and TEC (b) and delays between EUV and TEC (c) in hourly resolution. The black lines show the smoothed weekly means to present the overall trend (running mean with window size of 10 days)."

5. In Figure 4, the Kp index, the correlation coefficient and time delay show similar decreases during the end of each year. The authors indicated that the lower correlation coefficient and time delay should be related to the corresponding lower geomagnetic activity. Why the correlation coefficient is lower when the geomagnetic disturbance (Kp) is lower?

Answer: The explanation of annual variations of the correlation coefficients and ionospheric delay with geomagnetic activity is difficult and requires modeling efforts in the future. The topic introduces a lot of complexity due to the various ways geomagnetic activity impacts the ionospheric state. An explanation could be the global F2 layer ionization due to geomagnetic activity (Lal, C. (1992), Global F2 layer ionization and geomagnetic activity, J. Geophys. Res., 97(A8), 12153– 12159, doi:10.1029/92JA00325.).

As already suggested in the manuscript, analyses for longer time periods are required to further explain this relation and the processes behind it.

6. In Figures 11 and 12, the time delay generally does not change with latitude in winter. Whereas, during winter time the correlation coefficient is nearly 0 as seen in Figure 4. Therefore, the absolute values of the correlation coefficient should be provided in Figures 11 and 12.

Answer: We added the absolute correlation coefficients to Figures 11 and 12 and modify the captions accordingly.

Figure 13 (in previous version 11): "Map of the delay of TEC with respect to EUV in summer (May to August) and winter (November to February) within the time period from 2011 to 2014. The delay varies between ≈18.6 and ≈21.7 hours. The hatched regions on the map represent significantly greater (upper left to lower right fill) or smaller (upper right to lower left fill) correlations compared to the average of each map (± one standard deviation). The absolute correlation coefficient is ≈0.28 in summer and ≈0.17 in winter."

Figure 14 (in previous version 12): "Time series of the delay of TEC with respect to EUV as an epoch plot for the mid-latitudes covering Europe within the time period from 2011 to 2013. The delay varies between ≈11.3 and ≈23.1 hours. The absolute correlation coefficient is ≈0.21 during the period."

RC2:

1. Title and abstract

(Line 1) "...EUV radiation to analyse the delayed ionospheric response to test and improve previous studies on the ionospheric delay. Several..."

(Line 4) " ..the analysis at an hourly resolution..."

(Line 13) "...Results confirm that geomagnetic activity and the 11-year solar cycle
also affect the ionospheric response to solar EUV changes"

Alternatively, lines 6–14 could be re-written to more accurately summarise the conclusions.

Answer: We changed the abstract as suggested.

2. Major Issues and Questions

1 The motivation provided through GNNS in the introduction (around Line 25) is not appropriate. If the authors wish to continue with this motivation, the following issues need to be addressed:

(a) Not all terms are defined (e.g., a different definition of "high temporal resolution" is used on line 27 when compared to the rest of the paper).

(b) Citations to GNSS work are absent. The motivation would be strengthened by citations of articles that have proved high accuracy GNSS products require accurate ionospheric models, as well as citations to articles that highlight missing physics in ionospheric models when handling the ionospheric delay. Given studies such as Ren et al. (2018), which show that ionosphericmodels do capture the ionospheric delay to solar EUV irradiance, I would recommend that the authors find a different motivation for their study.

(c) Finally, this motivation also requires citations that demonstrate that other higher order GNSS correction issues (such as the bending terms) are not as important as the parts of the refractive index terms that would be affected by the (to have been) demonstrated issues with ionospheric models that are affected by the ionospheric delay.

Answer: We changed the motivation for our study:

Line 24: "The delayed ionospheric response to solar EUV radiation is captured in various ionospheric models (Ren et al., 2018; Vaishnav et al., 2018) and respective simulations can confirm results of previous studies estimating the ionospheric delay with observational data on daily resolution. The calculation of the delay with observational data in high temporal resolution (≤1 hour) is of interest to describe features like seasonal and spatial variations in more detail. The dependence on solar and geomagnetic activity (Ren et al., 2018) can be explored further. In the future, results for the ionospheric delay on high temporal resolution will strengthen the understanding of ionospheric processes and help to validate physics-based models."

2 The authors highlight the differences between the regions covered by the two ionospheric parameters used in this study. While it is true that GNSS TEC includes information about the entire ionosphere-plasmasphere system through which it travels, it is also true that the F2 region is responsible for most of variations in TEC (e.g., Petrie et al. 2011). Text and data interpretations would benefit from clarifying the relative contributions from the different ionospheric regions and

plasmasphere to the TEC, as well as the expected agreement between the column integrated plasma density and the critical frequency of the F2 layer based on past studies.

Answer: We added an explanation about the ionospheric and plasmaspheric contribution to TEC and clarify the dominant role of the F2 layer:

Line 47: “The variations of TEC are mostly controlled by the F2 layer (Lunt et al., 1999; Petrie et al., 2010; Klimenko et al., 2015) and for mid-latitudes the total plasmaspheric contribution to TEC is between approximately 8 to 15 % during daytime and approximately 30 % during nighttime (Yizengaw et al., 2008).”

We added a clarification for the high correlation between TEC and foF2, but also mention the difference of both parameters, which could result in different ionospheric delays.

Line 52: “Both ionospheric parameters are highly correlated (Kouris et al., 2004), but variations like different peak time of the diurnal variation (Liu et al., 2014) could have a considerable impact on the delayed ionospheric response.”

3 In the introduction, the authors do not sufficiently discuss the contributions of previous ionospheric delay studies. Specifically, there is no discussion as to the physical reason behind the ionospheric delay, although this has previously been investigated (e.g., Ren et al. 2018).

We added a summary of the recent investigations by Ren et al. 2018 to give an overview to the processes behind the delay:

Line 34: “The recent results by Ren et al. 2018 from observational and model calculations specified different features of the ionospheric delay. A strong impact of the geomagnetic activity on the ionospheric delay to solar EUV changes was found. Simulations with the Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM) and calculations were used to discuss the influence of ion production and loss as well as the impact of the O/N2 ratio. The ion production responds immediately to EUV variations and depends on both, the solar EUV flux contribution and the O/N2 ratio. The loss is delayed and controlled by the O/N2 ratio, which in turn is also dominated by the solar EUV flux contribution. The ionospheric response could further be modulated by dynamic and electrodynamic processes in the ionosphere. Ren et al. 2018 also showed a latitudinal dependence of the delay.”

4 A motivation behind using the European and Australian regions is needed. For example, why not use North and South America (see coverage for 1 January 2011 in the attached Figure)? This figure is included not to say that there is not a good reason to use European and Australian data, but to show that “good data coverage for Europe” is not a good reason in and of itself.

Answer: We added a reference to back our statement about data quantity/quality of TEC and ionosonde data for the European region:

Line 86: “The dense coverage of GPS stations over Europe allows a good comparison with TEC data for these locations (Belehaki et al., 2015).”

We clarified that not only the European region has good data coverage:

Line 49: “The availability of TEC in maps with good data coverage for certain regions (e.g. European or North American region) allows a spatial analysis of the delay and a comparison with the foF2 data for specific locations.”

We added magnetic declination and inclination in Table 2 and explain further, why a comparison between both regions seems appropriate:

Line 91: “The conditions of Earth's magnetic field for the European and Australian stations are comparable with small magnetic declination and similar absolute value of magnetic inclination (see Table 2). The selected stations seem appropriate for a comparison between northern and southern hemisphere due to these similar conditions.”

5 The authors state that they use two important ionospheric parameters that are appropriate to investigate the processes responsible for the ionospheric delay (data section), but they state in the conclusions that the processes for the delayed ionospheric response still need to be described. If the first statement is true, then an investigation of the underlying physical processes should be included in this paper. If such a study is beyond the scope of this paper, than the statements made about the ionospheric parameters used to study the characteristics of the ionospheric delay should be altered.

Answer: We changed the statement to clarify the actual use of the parameters in the study:

Line 70: “The analysis correlates EUV with two important ionospheric parameters, appropriate to investigate features of the ionospheric delay.”

6 The authors state that the TEC is more important than the foF2 but do not back up this valuation, especially since they say in the introduction that the ionospheric delay for the two parameters is very similar. The reason given, “TEC is...less sensitive to disturbances, such as plasma redistribution, than other parameters” is not substantiated. Additionally, since TEC is regularly used to study plasma redistribution (e.g., Foster 2008; doi:10.1029/181GM12) , the degree of sensitivity difference between TEC and foF2 needs to be shown to be significant (either by the authors or through appropriate referencing) for this valuation to be believable.

Answer: We changed the statement to clarify, why TEC is used:

Line 71: “The first parameter is TEC, which is an integral measurement of the electron density and well suited for the analysis of the ionospheric response to solar EUV variations. The parameter was used in several preceding studies to calculate the ionospheric delay (see Table 1).”

7 (Line 64) The resampling method needs to be described in more detail. Was an interpolation used? If so, between which points? Was the nearest value taken?

Answer: We clarified the process: the data were extracted from IGS TEC maps without any interpolation (spatial or temporal).

Line 78: “In preparation for the delay calculation, TEC values at seven ionosonde locations and one region (Europe) were extracted from the IGS TEC maps. For each ionosonde location the nearest grid point in the maps was used.”

8 (Line 67) What is the temporal resolution of the ionosonde data and were they hand scaled or autoscaled?

Answer: We clarified the temporal resolution and scaling of the ionosonde data:

Line 81: “The other ionospheric parameter included in the analysis, foF2, is derived from ionosonde station data (NOAA, 2019) provided by the National Oceanic and Atmospheric Administration (NOAA), and are available for the same time periods with temporal resolution of 15 minutes (Wright and Paul, 1981).”

Line 84: “In the northern hemisphere, the European stations Tromsø, Pruhonice, Rome, and Athens were selected (auto scaled), […]”

Line 89: “Instead data from the Australian stations Darwin, Camden, and Canberra for the analysis in the southern hemisphere are used (auto scaled).”

9 What is the effect of the difference in geographic longitude and magnetic location (including location relative to the auroral oval, declination, and inclination) on the locations in Europe and Australia?

Answer: We added the declination and inclination of each location to Table 1 showing again the similar conditions for the comparison between northern and southern hemisphere.
The specific conditions for Tromso (the only auroral station) are already explained in the manuscript.

10 (Line 76) How are data resampled in this instance? From the context, it appears that the authors are downsampling data from a minute-scale resolution to a one hour resolution, but this is unclear (especially since the same wording was used for a different process on line 64).

Answer: The wording for the method in line 64 was adjusted (see comment 7). We changed the description to clarify the use of the mean value to calculate the resampled data sets:

Line 94: “In preparation of the analysis, all data are resampled to an hourly resolution using the mean value […]”

11 (Line 90) A better explanation of why the correlation coefficient is still useful even though the values specify that the data sets being compared are uncorrelated is needed.

Answer: We added an explanation, why the analysis of times with high and low correlation coefficients between solar EUV and ionospheric parameters is useful/important:

Line 113: “The varying correlation between solar EUV flux or solar proxies like F10.7 with TEC is known from preceding studies. Solar EUV radiation is not able to describe the ionospheric variability at all time periods and on all time scales sufficient resulting in low correlation coefficients (Unglaub et al., 2012) and indicating a stronger impact of other processes (Verkhoglyadova et al., 2013). Analyzing both, times of high and low correlation between solar EUV flux and ionospheric parameters, is important to understand the changes of processes and interactions in the ionosphere on the whole.”

12 What data quality constraints were applied to the input and processed data? Why were periods when the data quality is stated to be poor included?

Answer: We didn't accept data into our analysis with data gaps for longer time periods (e.g. gaps of several days) or with periods with lots of smaller data gaps. The correlation coefficients were then calculated for the whole available time period to get an impression, how periods of poor data quality impact the results. In Figure 7 and 8 these periods are removed due to the uncertainty for the delay calculation.

13 The authors state that the ionospheric delays show a good correlation with the geomagnetic activity, but this is not demonstrated. If the authors believe that they have demonstrated this correlation, they should improve the clarity of the figure presentation and the text surrounding it.

Answer: We added a Figure comparing the gradient of the delay with the Kp-index and explain the modulation of the geomagnetic activity on the delay. The correlation coefficients in each year are 0.53 in 2011, 0.70 in 2012 and 0.77 in 2013 (see supplements).

14 (Line 184) The authors are quick to attribute differences between the TEC and foF2 ionospheric delays to differences between the F2 peak and the ionosphere-plasmasphere system, but there are other possibilities (including the background model used in the TEC calculation) that should be acknowledged or eliminated.

Answer: We clarified the concerns about other impacts causing the difference in TEC and foF2 results:

Line 212: “These results could indicate a strong seasonal variation of the ionospheric delay in the F2 layer compared to the whole ionosphere-plasmasphere system, but there are other possible sources for the difference (e.g. the background model of the IGS TEC maps).”

15 There appears to be an offset between solstice and equinox occurrence and the seasonal variations shown in (Figure 10). Why is this? Has it been seen before?

Answer: We marked solstice and equinoxes in the Figure. An offset for the difference in the delays doesn't appear consistently. In addition, such a detailed analysis of features in the seasonal variations requires model calculations to eliminate uncertainties due to the specific locations. This question could be addressed in future studies though.

16 Figures 7 and 8 show a lot of scatter at the individual stations. The analysis presented in section 5 makes claims about latitude variations based on these figures that do not appear to be significant, due to this scatter. This analysis would be improved by including another figure with delay differences between the sites or, possibly, by adding confidence bars (perhaps standard deviations) to the hourly delays in Figures 7 and 8.

Answer: We added a figure similar to the comparison between Rome and Canberra for Rome and Tromso (see supplement) to show the difference between the two stations and discuss the trend of the difference with latitude in more detail (especially in regards of the different variation with latitude in winter mentioned in comment 17):

Line 220: “Figure 12 shows the difference between the stations Rome and Tromso for both ionospheric parameters. The results for TEC show a greater or similar ionospheric delay for the station Rome compared to the station Tromso. There are only a few short time periods during winter with a greater ionospheric delay for the station Tromso. A stronger seasonal variation appears for the parameter foF2, but overall the ionospheric delay is still greater for the station Rome. The mean difference for results in Figure 12 is 1.08 hours for TEC and 0.52 hours for foF2. The changes with latitudinal dependence of the trends during winter are due to the stronger increase of the ionospheric delay for Rome during summer.”

17 (Line 191) The authors state that the latitudinal dependence in the European sector is not visible in the winter. However, Figure 7b shows a latitudinal variation that is perhaps clearer than that in the summer, just different.

Answer: We clarified, that there is a difference in winter (see comment 16).

18 How is the resampling for Figure 12 performed? Is a running period or binned week used? Clarify this analysis process so that others may reliably replicate these results.

Answer: We clarified that the weekly value is calculated with the mean:

Line 249: “The results are summarized with epoch plots in Figure 12 having a resolution of one week (mean value) to allow a better presentation of the long-term changes of the ionospheric delay.”

19 (Line 211) What about the winter variations? Does the longitudinal ionospheric delay variation have a seasonal variation at all? It seems likely that this lack of variation is related to the small range of magnetic declination over Europe, which leads to longitudinally similar ionospheric transport processes regardless of season. Whatever the authors believe the reason to be, it should be discussed.

Answer: We discuss the possible explanation of the lack of longitudinal variations with the similar declination for the whole European region:

Line 244: “The small and similar magnetic declination for the European region could be related to the small variations of the ionospheric delay with longitude. There is an influence of the magnetic declination on the mid-latitude ionosphere, which leads to similar longitudinal transport processes in all seasons (Zhan et al., 2012, 2013). This behavior has to be explored with observational data for different regions or modeling efforts in the future.”

20 The last sentence of the conclusions omits the work done by Ren et al. (2018). The article would be improved by a discussion of the results in the context of the physical mechanism presented in that article and also by providing a clearer motivation behind using the ionospheric delay to validate or improve physics-based models.

Answer: We changed our motivation and added an explanation of the work by Ren et al. (2018) in our introduction (see comment 1 and 3).

3. Figures and tables

1 (Table 1 caption): “...provide an approximate ionospheric delay to solar activity at a daily resolution.

Answer: We changed the description according to the suggestion.

2 (Figure 1): This figure would benefit by over-plotting magnetic field information (such as the IGRF declination or at the hmF2) and the geomagnetic equator.

Answer: We plot the magnetic field information in the figure with data from the World Magnetic Model provided by NASA.

3 (Table 2): Which magnetic coordinate system is used for the geomagnetic coordinates?

Answer: We added magnetic declination and inclination to the Table. All magnetic parameters are calculated with the IGRF.

4 (Figure 2): Rows should be labeled with “Weekly”, “Daily”, and “Hourly”

Answer: We added the labels to the figure.

5 (Figure 2 caption): “...data, as well as the resulting correlation coefficients (red), for...”

Answer: We changed the caption.

6 (Figure 10): Mark the locations of the equinoxes and solstices.

Answer: We marked equinoxes and solstices and add a discussion (see major comment 15).

7 (Figure 11): Mark the locations of the European stations, to improve comparisons between Figure 11 and Figure 7.

Answer: We added marks for the locations of the European stations.

4. Grammar and organisation

1 Throughout the paper both 3rd person and impersonal tenses are used. This should be changed so that the tense throughout the article is consistent

Answer: We removed the use of the 3rd person.

2 Throughout the paper approximations are used for numbers that do not need them (e.g., the locations on Line 95 specify the approximate location of Rome and this is already appropriately expressed by limiting the number of significant figures)

Answer: We removed the use of approximations for numbers that don’t need them.

3 (Lines 27,) “which” should either be preceded by a comma or replaced with “that”
4 (Line 17) “dominating” should be “dominant
5 (Line 20) “...ionospheric variations that may depend on time or location.”
6 (Line 21) “...in the solar spectrum’...’. This change is necessary because the authors, in this sentence, are referring to the entire ionosphere, which means that X-rays and higher energy irradiance that impact the D and E regions are also important.
7 (Line 22) “...and composition at specific...”
8 (Line 23) “...electron density distribution. An understanding of the ionospheric chemical and physical processes is important, since...”
9 (Line 28) remove duplicated text “is needed”
10 (Line 32) “...have revealed that ionospheric parameters have a delayed response to solar variability. A selection of these studies...”
11 (Line 33) “...was calculated using different EUV proxies or measurements of the EUV flux at daily resolutions.”
12 (Line 35) “...the delay at a higher temporal resolution of one hour. Furthermore, we examine the hemispheric dependence of the ionospheric delay with a detailed study of the European region.”
13 (Line 37) “is made based on” should be “uses”
14 (Line 37) “The” needed before “Time series”
15 (Line 43) “...the ionosphere without complicating contributions from the plasmasphere and lower ionospheric layers. As expected, the results...
16 (Lines 45-47) This text belongs in the data or analysis section, not the introduction.

Answer: We changed the manuscript according to the suggestions.

17 (Data) This section would benefit by subsections for either the different data sources or between the presentation of the data sources and the data analysis techniques

Answer: We added two subsections: “Solar EUV radiation” and “Ionospheric parameters”.

18 (Line 49) “...spectrum have been continuously measured since 2000 C.E., with EUV observational data publicly available from...”
19 (Line 55) “...have a temporal resolution of 20 seconds. EVE data also cover several years (2011 to 2014)...
20 (Line 106) Description of the IGS TEC maps belongs in the Data section.
21 (Line 108) remove comma between “show” and “that”
22 (Line 109) “...be calculated at an hourly resolution for fixed...”
23 (Line 123) The sentence, “Se do not see any...different variations” is confusing and should be rewritten.
24 (Line 124) “...keeping in mind that their magnitude may differ due to...”
25 (Line 128) “...in Table 1. For example, Jakowski et al. (1991) used the...”
26 (Line 129) “...satellite-based EUV-TEC measurements (Unglaub et al., 2011) and also calculated the delay with EUV fluxes. The validation with EVE EUV flux measurements was important because the solar rotation variations...”
27 (Line 135) The first two sentences of this paragraph belong in the introduction. The remaining sentences belongs in the data section.

Answer: We changed the manuscript according to the suggestions.

28 (Line 138) Which calculation are the authors referring to?

Answer: We clarified that the calculation of the ionospheric delay is referred to.

29 (Line 144) “...negative values. In Figure 4, this was interpreted as a possible effect of geomagnetic activity.”
30 (Line 145) “...time period, the correlation coefficient drops due to data gaps and the applied interpolation method. (start new paragraph after this sentence)”
31 (Line 146) “...are smaller than those of the TEC. However, the trends of the two correlation coefficients are similar for the...”
32 (Line 148) “...Tromsø again show that the largest deviation from...”
33 (Line 152) “The TEC and foF2 correlation coefficients for the Australian stations are shown in Figure 6. In general, the Australian correlation...”
34 (Line 155) “...these results. Most notably, the decrease and...”

Answer: We changed the manuscript according to the suggestions.

35 (Line 156) Which seasonal variations do the authors expect to be impactful? Referencing is appropriate but the text description should be slightly more detailed.

Answer: We clarified which thermospheric conditions and season variations are meant:

Line 183: “The difference might be due to further impacts on the correlation, e.g. thermospheric wind conditions or seasonal variations due to composition changes (atomic/molecular ratio), which are not covered in this study, […]”

36 (Line 174) “...the delay at a daily resolution for longer time periods than the one used in this study.”

Answer: We changed the manuscript according to the suggestions.

37 (Line 175) The sentence is unclear and needs to be reworded.
38(Line 179) What do the authors mean by “global trend”?
39 (Line 179) The sentence is unclear and needs to be reworded.

Answer: We clarified the sentences:

Line 204: “The difference between the ionospheric delay for the European and Australian stations in Figures 7 and 8 show only small differences due to the assumed trend with the geomagnetic activity. This trend has to be removed in the further analysis. […]The non-seasonal trends are removed by calculating the difference between the ionospheric delays of both stations.”

40 (Line 183) “...a stronger seasonal variation...”
41 (Line188) “...with latitude in northern summer. The station at...”
42 (Line 193) remove “where data from high latitudes are missing” because the Australian stations have a larger low-latitude extent than the European stations and this phrase does not reflect that.
43 (Line 194) recommend replacing “agree” with “are consistent”

44 (Line 197) “...good observational coverage...”
45 (Line 198) Remove repeated description of the IGS TEC map
46 (Line 202) “...Figure 11, which maps the mean delay values for the mid-latitudes in summer (May-August) and winter (November-February). Figure 11 shows delays that are consistent with the results from the European ionosonde stations (Figure 7b).
47 (Line 205) “...hours over the entire region.”

Answer: We changed the manuscript according to the suggestions.

48 (Line 205) The sentence that begins at the end of this line is unclear and needs to be reworded.

Answer: We clarified the sentence and add a reference to preceding studies to back up our discussion:

Line 237: “The decrease of the ionospheric delay at latitudes greater than 65°N and smaller 35°N confirms a latitudinal trend, which was found in preceding studies (Lee et al., 2012).”

49 (Line 207) “...the delay decreases with increasing latitude. From...”
50 (Line 208) “...70◦N, or about -0.06 hours per degree in latitude.”
51 (Line 211) “...is much smaller than the variation in latitude for the same season, with a change of...”
52 (Line 224) “...main analysis, we confirmed...”
53 (Line 234) Move the last two bullet points starting on this line to the previous paragraph where the authors were discussing the portions of previous studies that this study validated.
54 (Line 242) “Future analysis would benefit from high resolution ionospheric delay calculations for longer time periods that cover different...”

Answer: We changed the manuscript according to the suggestions.

55 (Line 243) Sentence starting at the end of this line is unclear and needs to be reworded

Answer: We clarified the suggestion of including the thermospheric conditions in future analysis:

Line 279: “The thermospheric conditions (e.g. neutral winds or composition changes in the atomic/molecular ratio), which are known for their impact on the ionosphere (Rishbeth, 1998; Rishbeth et al., 2000) should be included in future analysis as well.”

56 (Data availability and acknowledgements) Not all acronyms are defined
57 (Line 297) “F 2” should be “F2”
58 (Line 327) page numbers missing and filled using n/a–n/a

Answer: We changed the manuscript according to the suggestions.

5. Referencing

1 Reference needed for the impact of solar irradiance on the vertical ionospheric structure

Answer: We added the reference: M. Kelley, The Earth’s Ionosphere, vol. 96. Academic Press, 2009.

2 (Line 44) Citation to a source that explains or demonstrated that TEC is dominated by the F2 peak response is needed

Answer: We added the reference (see major comment 2): Elizabeth J. Petrie and Manuel Hernandez-Pajares and Paolo Spalla and Philip Moore and Matt A. King, “A Review of Higher Order Ionospheric Refraction Effects on Dual Frequency GPS,” Surveys in Geophysics, vol. 32, no. 3, pp. 197–253, Nov. 2010.

3 (Line 63) Which model is included in the TEC calculation? Include a very short description and a citation to this model.

Answer: We added the references and move the model description to line 76:

Orus, “Improvement of global ionospheric VTEC maps by using kriging interpolation technique,” Journal of Atmospheric and Solar-Terrestrial Physics, vol. 67, no. 16, pp. 1598–1609, Nov. 2005.

M. Hernandez-Pajares et al., “Comparing performances of seven different global VTEC ionospheric models in the IGS context,” in IGS Workshop 8-12 February 2016, 2016.

4 (Line 106) Citation for IGS TEC maps needed.

Answer: We added the references for the IGS TEC maps.

5 (Line 196) Citation needed.

Answer: We added the references:

C. Watson, P. T. Jayachandran, and J. W. MacDougall, “GPS TEC variations in the polar cap ionosphere: Solar wind and IMF dependence,” Journal of Geophysical Research: Space Physics, vol. 121, no. 9, pp. 9030–9050, Sep. 2016.

N. Maruyama, “Dynamic and energetic coupling in the equatorial ionosphere and thermosphere,” Journal of Geophysical Research, vol. 108, no. A11, 2003.

Spatial and seasonal effects on the delayed ionospheric response to solar EUV changes

Erik Schmölter[1], Jens Berdermann[1], Norbert Jakowski[1], and Christoph Jacobi[2]

[1]German Aerospace Center, Kalkhorstweg 53, 17235 Neustrelitz, Germany
[2]Leipzig Institute for Meteorology, Universität Leipzig, Stephanstr. 3, 04103 Leipzig, Germany

Correspondence: Erik Schmölter (Erik.Schmoelter@dlr.de)

Abstract. This study correlates different ionospheric parameters with the integrated solar EUV radiation ~~for an analysis of~~ to analyze the delayed ionospheric response ~~in order to confirm~~ to test and improve previous studies on the ~~delay and to further specify variations of the delay~~ionospheric delay. Several time series for correlation coefficients and delays are presented to characterize the trend of the delay from January 2011 to December 2013. The impact of the diurnal variations of ionospheric parameters in the analysis ~~on~~ at an hourly resolution for fixed locations are discussed and specified with calculations in different time scales and with comparison to solar and geomagnetic activity. An average delay for TEC of ≈ 18.7 hours and for foF2 of ≈ 18.6 hours is calculated at four European stations. Through comparison with the Australian region the difference between northern and southern hemisphere is analyzed and a seasonal variation of the delay between northern and southern hemisphere is calculated for TEC with $\approx 5 \pm 0.7$ hours and foF2 with $\approx 8 \pm 0.8$ hours. The latitudinal and longitudinal variability of the delay is analyzed for the European region and a decrease of the delay from ≈ 21.5 hours at 30°N to ≈ 19.0 hours at 70°N has been found. For winter months a roughly constant delay of ≈ 19.5 hours is calculated. In this study a North-South trend of the ionospheric delay during summer month has been observed with ≈ 0.06 hours per degree in latitude. The results based on solar and ionospheric data in hourly resolution and the analysis of the delayed ionospheric response to solar EUV show the seasonal and latitudinal variations. Results also indicate the dependence on the geomagnetic activity as well as on the 11-year solar cycle.

1 Introduction

The solar extreme ultraviolet radiation (EUV) is the ~~dominating~~ dominant source of ionization in the ionosphere. Therefore, the high variability of EUV within the 27-day solar rotation cycle, the 11-year solar cycle, or within short-term events like solar flares (Berdermann et al., 2018) has a strong impact on the ionosphere. The resulting photoionization, together with photodissociation, recombination, and transport processes, causes different ionospheric variations ~~, which can be time- or location-dependent~~that may depend on time or location. The structure of the ionosphere is dominated by the interaction of

Publication	Delay [d]	Solar flux parameter	Ionospheric parameter
Titheridge (1973)	1	F10.7	TEC
Jakowski et al. (1991)	1-2	F10.7	TEC
Jakowski et al. (2002)	1-3	F10.7	TEC
Afraimovich et al. (2008)	1.5-2.5	F10.7, EUV	Global mean TEC
Oinats et al. (2008)	2-4	F10.7	NmF2, TEC
Zhang and Holt (2008)	2-3	F10.7	Electron density
Min et al. (2009)	2	F10.7	Electron density, TEC
Lee et al. (2012)	1-2	F10.7	Electron density
Jacobi et al. (2016)	1-2	F10.7, EUV	Global mean TEC
Ren et al. (2018)	1	EUV	Electron density

Table 1. The table presents results from former studies, which provide ~~a first rough information (daily resolution) of the~~ an approximate ionospheric delay to ~~the~~ solar activity at a daily resolution.

different wavelength ranges in the ~~EUV~~ solar spectrum with the respective particle population and composition ~~in~~ at specific altitudes. This results in different ionospheric layers defined by the density distribution of the ion species (Kelley, 2009). An understanding of ~~these~~ the ionospheric chemical and physical processes ~~in the ionosphere is important , since many modern navigation, communication, and land surveying applications rely on precise positioning based on Global Navigation Satellite Systems (GNSS). GNSS performance is strongly influenced by radio signal propagation through the dynamic ionosphere. Therefore, satellite navigation applications require realistic ionospheric models in order to predict ionospheric changes~~ is important to provide realistic and reliable physics-based models. The delayed ionospheric response to solar EUV radiation is captured in various ionospheric models (Ren et al., 2018; Vaishnav et al., 2018) and respective simulations can confirm results of previous studies estimating the ionospheric delay with observational data on daily resolution. The calculation of the delay with observational data in high temporal ~~and spatial resolution. The exact information on the electron content is needed which is needed to correct the ionospheric influence on GNSS positioning. Detailed knowledge about the ionospheric reaction to solar EUV can directly contribute to the improvement of ionospheric models and give a better understanding of the physical processes involved~~resolution ($\leq$1 hour) is of interest to describe features like seasonal and spatial variations in more detail. The dependence on solar and geomagnetic activity (Ren et al., 2018) can be explored further. In the future, results for the ionospheric delay on high temporal resolution will strengthen the understanding of ionospheric processes and help to validate physics-based models.

Former analyses of the ionospheric electron content changes in connection with solar flux variations, in particular on the 27-day rotation time scale, have revealed ~~a delay of ionospheric parameters with respect~~ that ionospheric parameters have a delayed response to solar variability. A selection of these studies is presented in Table 1. In these studies, the ionospheric delay was calculated ~~based on different proxies and EUV flux data, with only a rough estimate ranging between one and three days (daily resolution) .~~ using different EUV proxies or measurements of the EUV flux at daily resolutions. The recent results by Ren et al. (2018) from observational and model calculations specified different features of the ionospheric delay. A strong impact of the geomagnetic activity on the ionospheric delay to solar EUV changes was found. Simulations with the Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM) and calculations were used to discuss the influence of ion production and loss as well as the impact of the O/N$_2$ ratio. The ion production responds immediately to EUV variations and depends on both, the solar EUV flux contribution and the O/N$_2$ ratio. The loss is delayed and controlled by the O/N$_2$ ratio, which in turn is also dominated by the solar EUV flux contribution. The ionospheric response could further be modulated by dynamic and electrodynamic processes in the ionosphere. Ren et al. (2018) also showed a latitudinal dependence of the delay.

~~In this study we analyze~~ This study analyzes the delay in high temporal resolution of one hour. Furthermore, ~~we give an overview about the expected variations in the delayed ionospheric response in the northern and southern hemisphere in general with an additional more detailed focus on~~ the hemispheric dependence of the ionospheric delay is examined with a detailed study of the European region. This analysis ~~is made based~~ uses on GNSS and ionosonde data over Europe and Australia. ~~Time~~ The time series of the delays and the correlation coefficients are calculated between solar EUV radiation and two ionospheric parameters: the Total Electron Content (TEC) and the critical frequency of the F2 layer (foF2). TEC measures the vertical integrated electron density and can be used to describe changes in the whole ionosphere-plasmasphere system due to solar EUV variability. The variations of TEC are mostly controlled by the F2 layer (Lunt et al., 1999; Petrie et al., 2010; Klimenko et al., 2015) and for mid-latitudes the total plasmaspheric contribution to TEC is between approximately 8 to 15 % during daytime and approximately 30 % during nighttime (Yizengaw et al., 2008). The availability of TEC in maps with good data coverage for certain regions (e.g. ~~Europe~~European or North American region) allows a spatial analysis of the delay and a comparison with the foF2 data for specific locations. On the other hand, foF2 describes only the F2 layer of the ionosphere ~~and there is no dependence to other regions in the upper atmosphere compared to TEC. Nevertheless, we~~ without complicating contributions from the plasmasphere and lower ionospheric layers. Both ionospheric parameters are highly correlated (Kouris et al., 2004), but variations like different peak time of the diurnal variation (Liu et al., 2014) could have a considerable impact on the delayed ionospheric response. As expected, the results will show that the ~~results for the delay are~~ ionospheric delay is very similar for ~~both ionospheric parameters~~TEC and foF2.

2 Data

In preparation for the analysis, ~~we discuss the~~ the data itself, but also problems and challenges of using data with hourly resolution and ~~which impacts the~~ the impact of the diurnal variations in the ionospheric parameters ~~have~~ on the cross-correlations are discussed. This discussion is crucial for the interpretation of the calculated delays.

3 ~~Data~~

2.1 Solar EUV raidation

Parts of the EUV spectrum has been continuously measured since ~~the year~~ 2000 ~~and~~ C.E., with EUV observational data ~~can be accessed~~ publicly available from the Solar EUV Experiment (SEE) onboard the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite (Woods et al., 2005), the Geostationary Operational Environmental Satellites (GOES) (Machol et al., 2016), or the Solar Auto-Calibrating EUV/UV Spectrophotometers (SolACES) (Nikutowski et al., 2011; Schmidtke et al., 2014). The data used in this paper are from the Solar Dynamics Observatory (SDO) EUV Variability Experiment (EVE) (LASP, 2019). They represent almost the whole EUV spectrum (wavelength range from 0.1 to 105 nm with a spectral resolution of 0.1 nm) and have ~~the required high resolution of at least one hour for the delay analysis (~~a temporal resolution of 20 seconds~~)~~. EVE data also cover ~~a long time period~~ several years (2011 to 2014) without large data gaps (Woods et al., 2012).

~~In the analysis , we correlate~~

2.2 Ionospheric parameters

The analysis correlates EUV with two important ionospheric parameters, appropriate to investigate ~~the processes responsible for the~~ features of the ionospheric delay. The first ~~and most important~~ parameter is TEC, which is an integral measurement of the electron density and well suited for the analysis of the ionospheric response to solar EUV variations. ~~TEC is an integral measurement of the electron density and less sensitive to disturbances, such as plasma redistribution, than other parameters~~The parameter was used in several preceding studies to calculate the ionospheric delay (see Table 1). The time series of TEC for single locations and regions is extracted from the International GNSS Service (IGS) TEC maps (NASA, 2019b), which provide coverage since 1998 with the required high resolution of at least one hour (Hernández-Pajares et al., 2009). These TEC data represent a weighted average between real observations and an ionospheric model, dependent on the availability of observations at a given time and location. The chosen IGS TEC maps by Universitat Politècnica de Catalunya (UPC) use a global voxel-defined 2-layer tomographic model solved with Kalman filter and spline interpolation (Orús et al., 2005; Hernández-Pajares et al., 2016) . In preparation for ~~calculating the delay~~ the delay calculation, TEC values at seven ionosonde locations and one region (Europe) were ~~resampled from the TEC maps, where the values of the~~ extracted from the IGS TEC maps. For each ionosonde location the nearest grid point ~~were extracted for each location~~in the maps was used.

The other ionospheric parameter included in the analysis, foF2, is derived from ionosonde station data (NOAA, 2019) provided by the National Oceanic and Atmospheric Administration (NOAA), and are available for the same time periods with ~~high temporal resolution~~ temporal resolution of 15 minutes (Wright and Paul, 1981). Figure 1 shows a map of stations used to calculate the ionospheric delay. The geographic and geomagnetic latitudes and longitudes of the stations are shown in Table 2. In the northern hemisphere, the European stations Tromsø, Průhonice, Rome, and Athens were selected (auto scaled), since they cover different latitudes ranging from ≈ 38°N to ≈ 70°N. The dense coverage of GPS stations over Europe allows a good comparison with TEC data for these locations (Belehaki et al., 2015). An analysis of the southern hemisphere with the South

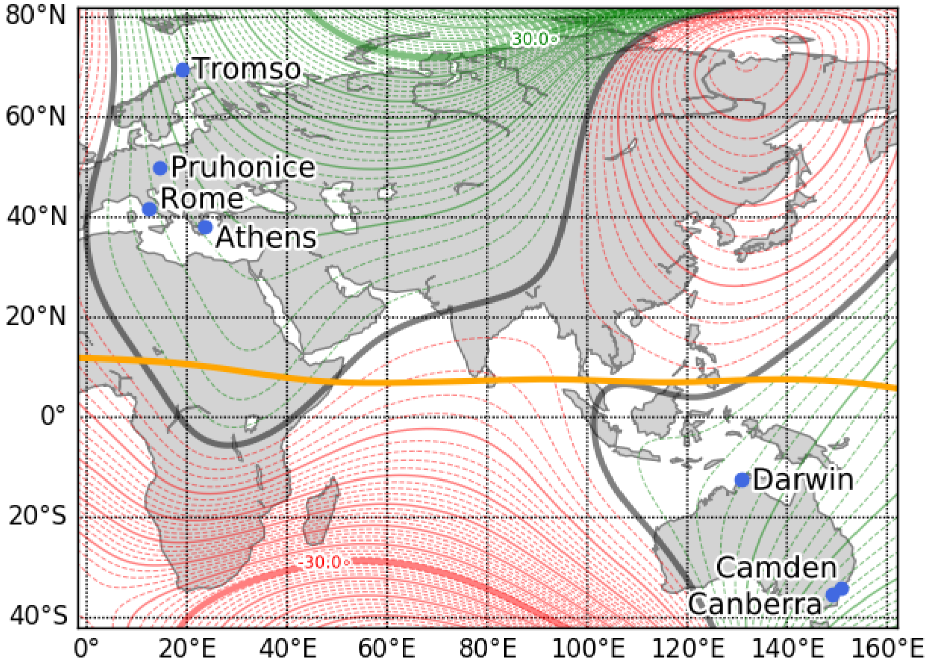

Figure 1. The European (Tromsø, Průhonice, Rome and Athens) and Australian (Darwin, Camden, Canberra) ionosonde stations which are used in the calculation of the delayed response of the ionosphere to solar EUV variations. Earth's magnetic field is presented with the geomagnetic equator (orange line) and the magnetic declination (green, red and black lines) from the World Magnetic Model (NASA, 2019c) .

African region would be preferred because of a similar longitude, but there are some time and data gaps, which prevented a reliable estimation of the delay for the available stations. Instead ~~we use~~ data from the Australian stations Darwin, Camden, and Canberra for the analysis in the southern hemisphere are used (auto scaled). These stations cover latitudes between ≈ 12°S to ≈ 35°S. The conditions of Earth's magnetic field for the European and Australian stations are comparable with small magnetic declination and similar absolute value of magnetic inclination (see Table 2). The selected stations seem appropriate for a comparison between northern and southern hemisphere due to these similar conditions. The variability of the characteristic ionosphere parameter foF2 measured with ionosondes are compared to the EUV flux. In preparation of the analysis, all data are resampled to an hourly resolution using the mean value and gaps are filled with a linear interpolation. Unlike in Schmölter et al. (2018), there are no band-stop filters to reduce the daily variations, since this calculation step does not add more reliability to the delay calculation. The Kp-index (NASA, 2019a) is used to characterize the influence of the geomagnetic activity on the delay in the analysis.

Station	geographic [°]		geomagnetic [°]		magnetic [°]	
	Lat.	Lon.	Lat.	Lon.	Dec.	Inc.
Tromsø	69.7	19.0	~~67.0~~ 67.2	~~117.5~~ 115.9	7.0	78.2
Průhonice	50.0	14.6	~~49.7~~ 49.3	~~98.5~~ 98.6	2.9	65.9
Rome	41.8	12.5	~~42.3~~ 41.8	~~93.2~~ 93.6	2.2	58.0
Athens	38.0	23.6	~~36.4~~ 36.2	~~102.5~~ 103.3	3.7	54.5
Darwin	-12.4	130.9	~~-22.9~~ -21.5	~~-157.3~~ -155.7	3.3	-39.7
Camden	-34.0	150.7	~~-42.0~~ -40.1	~~-132.4~~ -131.6	12.4	-64.5
Canberra	-35.3	149.0	~~-43.7~~ -42.3	~~-134.3~~ -133.2	12.3	-66.0

Table 2. Geographic and geomagnetic latitudes and longitudes of the European (Tromsø, Průhonice, Rome and Athens) and Australian (Darwin, Camden, Canberra) ionosonde stations which are used in the calculation of the delayed response of the ionosphere to solar EUV variations. The magnetic declination and inclination are shown as well. The magnetic field parameters are calculated with the International Geomagnetic Reference Field (NASA, 2019d).

3 Correlation of ionospheric parameters with solar EUV

The delayed ionospheric response to solar variability was calculated by different studies in daily resolution. A selection of these studies are shown in Table 1. A first delay calculation with cross-correlations in hourly resolution was done by Schmölter et al. (2018). Here ~~we extend previous research~~ the previous research is extended by addressing daily and seasonal as well as regional dependencies of the ionospheric delay in high temporal resolution. In the analysis different locations are compared and corresponding time series for ionospheric parameters include different variations: diurnal variations, 27-day solar rotation cycle, seasonal variations. Figure 2 shows the impact of the diurnal variations on the correlation coefficients by comparing different temporal resolutions (weekly, daily, hourly). The TEC data in hourly resolution are extracted from IGS TEC maps (NASA, 2019b) at the location of Rome (~~≈ 41.8°N and ≈ 12.5°~~41.8°N and 12.5°E). The EUV data are integrated SDO-EVE fluxes from 6 to 105 nm (LASP, 2019). The daily and weekly data sets for TEC are retrieved by calculating the corresponding means for the values from 11:00 to 13:00 each day, i.e. only the time periods with an expected maximum photoionization are considered. The correlation coefficients between EUV and TEC data are calculated using a time window of approximately 90 days. The comparison of correlation coefficients in hourly and weekly resolution in Figure 2 shows that the correlation on hourly resolution is, as expected, much smaller. Increases and decreases of the correlation coefficients have the same trend though. A characterization of the correlation trend is possible in all shown resolutions. The varying correlation between solar EUV flux or solar proxies like F10.7 with TEC is known from preceding studies. Solar EUV radiation is not able to describe the ionospheric variability at all time periods and on all time scales sufficient resulting in low correlation coefficients (Unglaub et al., 2012) and indicating a stronger impact of other processes (Verkhoglyadova et al., 2013). Analyzing both, times of high and low correlation between solar EUV flux and ionospheric parameters, is important to understand the changes of processes and interactions in the ionosphere on the whole.

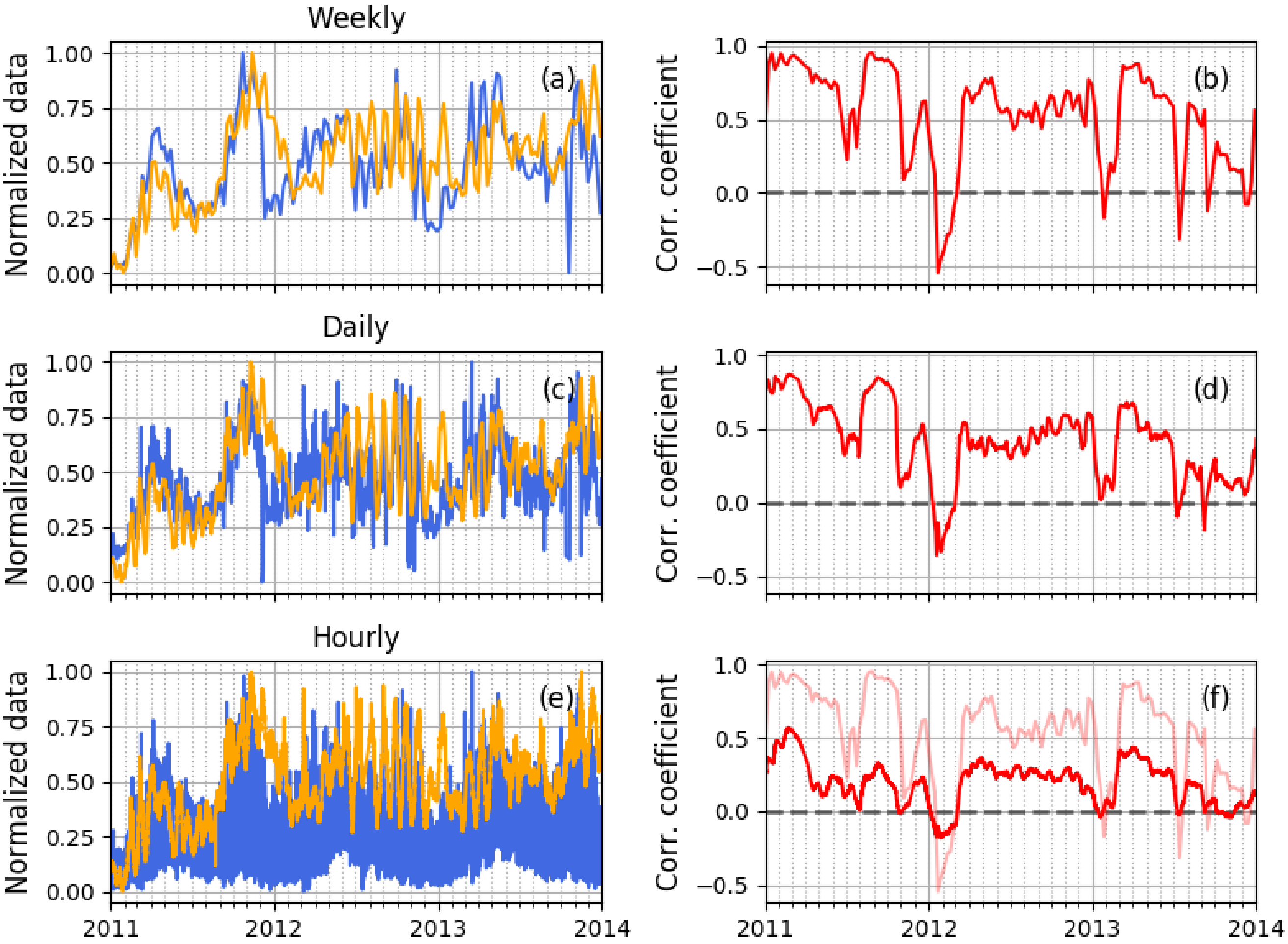

Figure 2. The plots show the normalized TEC (blue) and EUV (orange) data, as well as the resulting correlation coefficients (red), for different temporal resolutions: weekly (a, b), daily (c, d) and hourly resolution (e, f). The correlation coefficients were calculated using a time window of approximately 90 days and a step size corresponding to each resolution. The daily and weekly TEC data were retrieved by calculating the mean for the values from 11:00 to 13:00 local time each day. The correlations coefficients for the weekly resolution are shown in the plot for the hourly resolution again (light red). All data correspond to the location of Rome with ~~≈ 41.8°~~41.8°N and ~~≈ 12.5°~~12.5°E.

In Figure 3 the correlation coefficients and delay between TEC and EUV are shown for a fixed location (Rome with a latitude of ~~≈ 41.8°~~41.8°N and a longitude of ~~≈ 12.5°~~12.5°E) and a fixed local time (12:00) at the same latitude (40°N). The correlation coefficients and delay for both results are calculated with cross-correlations using a time window of approximately 90 days with the TEC and EUV data. The difference between both methods is the extraction of the TEC time series from the TEC maps. For the calculation with fixed location the latitude and longitude are unchanged for each data point. For the calculation with fixed local time the longitude is changed to correspond with the location at 12:00 local time. In Figure 3 the differences

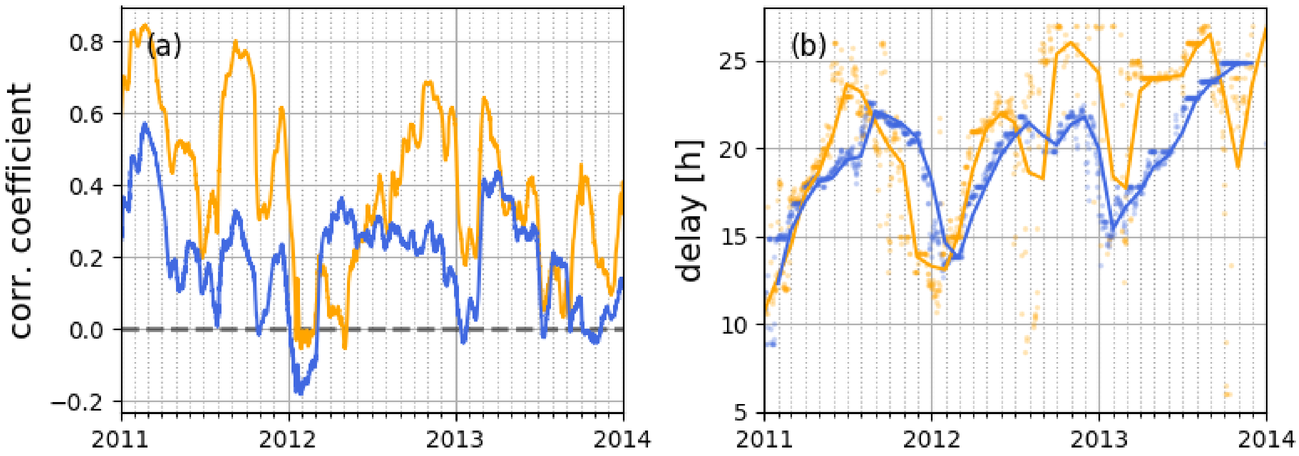

Figure 3. Plot (a) shows the correlation coefficients and plot (b) the delays calculated with a fixed location (blue) and a fixed local time (orange). The fixed location is Rome (~~≈ 41.8°~~41.8°N and ~~≈ 12.5°~~12.5°E) and the fixed local time is 12:00 at 40°N. The correlation coefficients and delays were calculated using a time window of approximately 90 days and a step size of 1 hour with TEC and EUV data. The delays in hourly resolution are shown by dots and the monthly means of the delays are shown as solid lines.

of the correlation coefficients are shown. The correlation coefficients for a fixed local time are greater than for a fixed location, but strong increases or decreases of the trend appear in both data sets (e.g. the strong decreases in the end of 2011 and 2012). The trend of the delay with a slight increase over the three years as well as the annual variation are present. The two different approaches have a mean variance of approximately 3.15 hours, which accounts for an uncertainty of approximately 16.04 % in the ionospheric delay calculation. This is an acceptable impact of the diurnal variation on the trend of the delay ~~is negligible for a characterization~~for characterizing temporal and spatial changes.

The delayed ionospheric response to solar EUV radiation depends on the solar local time and the calculated results for fixed locations can be understood as a mean ionospheric delay for different local times. The local time approach would be preferred for this reason. Nevertheless, the analysis with fixed local time is not used in the further analysis, since the extracted time series from the IGS TEC maps relies less on measurements considering areas with few or no ground stations. The time series have a certain dependence on the underlying model~~(for the chosen IGS TEC maps by Universitat Politèecnica de Catalunya (UPC), a global voxel-defined 2-layer tomographic model solved with Kalman filter and spline interpolation)~~. Despite of the strong diurnal variations in the ionospheric parameters and their impact on the correlation and the delay calculation, Figures 2 and 3 show ~~,~~that relative trends can be calculated ~~in~~ at an hourly resolutions for fixed locations. The significant decreases of the correlation and the negative correlation coefficients are not effects of the diurnal variations, since they are in the same order for all results and the observed trend must have another origin (see Figures 2 and 3).

Geomagnetic activity and thermospheric conditions have an additional impact on the ionospheric state as well. In the chosen time period from January 2011 until ~~2014~~ Decemeber 2013 for this study (during a solar minimum) a stronger impact of the

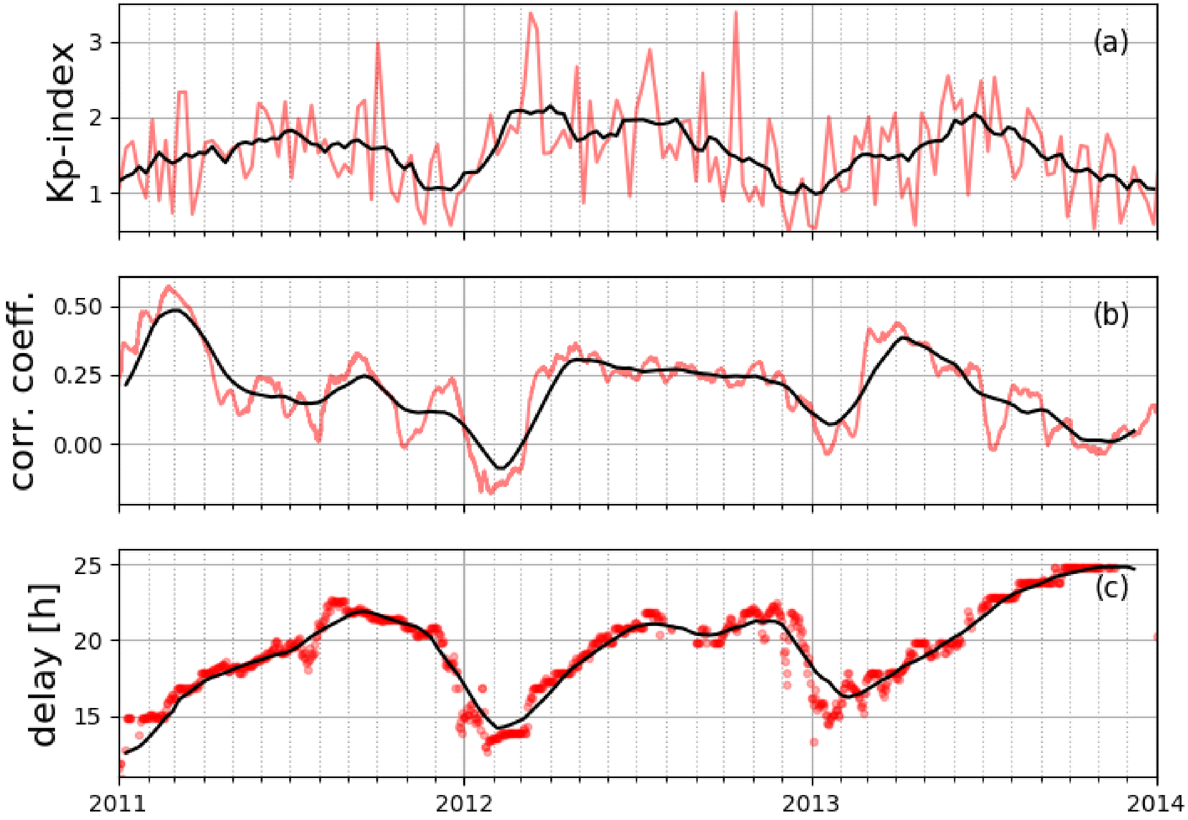

Figure 4. The transparent red lines or dots show the raw data: Kp-index in weekly resolution (a), correlation ~~coefficient~~ coefficients between EUV and TEC (b) ~~, delay~~ and delays between EUV and TEC (c) in hourly resolution. ~~In each plot the transparent red line or dots~~ The black lines show the ~~raw data and the black line~~ smoothed weekly means to present the overall trend (running mean with window size of 10 days). All data correspond to the location of Rome with ~~≈ 41.8°~~ 41.8°N and ~~≈ 12.5°~~ 12.5°E.

geomagnetic activity can be expected (Zieger and Mursula, 1998). These variations are not covered by EUV flux measurements and cannot be characterized with the cross-correlations between solar EUV and ionospheric parameters. In Figure 4 the calculated correlation coefficients and delay from the location Rome (already shown in Figure 3) are compared to the Kp-index as a measure of the geomagnetic activity. The smoothed trends of the Kp-index, correlation coefficient between EUV and TEC as well as delay between EUV and TEC show similar decreases in all three data sets during the end of each year. The minimum of the correlation coefficient and the delay are about two month behind the minimum of the Kp-index. The comparison of the Kp-index with the gradient of the delay in Figure 5 shows good correlations for each year (≈ 0.53 in 2011, ≈ 0.70 in 2012

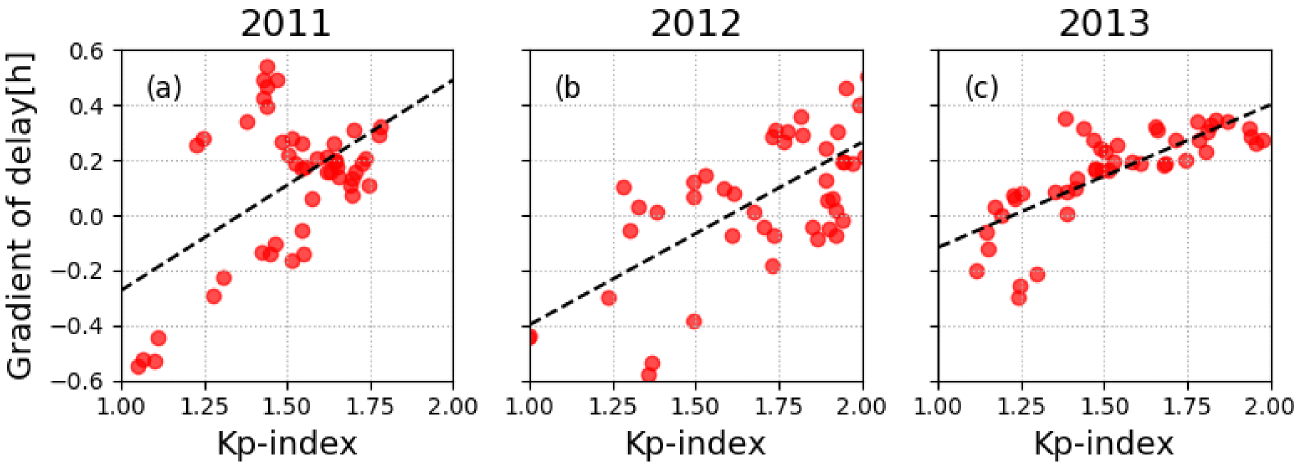

Figure 5. The scatter plots for 2011 (a), 2012 (b) and 2013 (c) show the correlation between the Kp-index and gradient of the delay. The smoothed weekly means (running mean with window size of 10 days) are used for this comparison. Correlation coefficients of ≈ 0.53 (a), ≈ 0.70 (b) and ≈ 0.77 (c)are estimated.

and ≈ 0.77 in 2013) indicating that the geomagnetic activity modulates the ionospheric delay. The strong impact of the geomagnetic activity on the delay was reported e.g. by Ren et al. (2018), and ~~Figure 4 gives~~ Figures 4 and 5 give a first indication about such a relation. ~~In the further analysis , we~~ The further analysis will show similar results for the southern hemisphere, confirming this behavior as a global trend in the mid-latitudes.

In conclusion, the results in Figures 2, 3 and 4 show that the diurnal variations have ~~a~~ an impact on the correlation between EUV and TEC on hourly resolution. ~~We do not see any~~ There is no significant changes in the trend and ~~get~~ the information about different variations ~~. In the following analysis we~~ can be retrieved. The following analysis will characterize certain variations, while keeping in mind ~~,~~ that their magnitude ~~might be several values off~~ may differ due to the deviations caused by the diurnal variations.

4 Representation of the delay for TEC and foF2

In earlier studies, the correlation of the ionospheric delay has been calculated for different ionospheric parameters based on daily or hourly resolutions, as shown in Table 1. ~~Jakowski et al. (1991), for example,~~ For example, Jakowski et al. (1991) used the solar radio flux index F10.7 and calculated a delay of one to two days. Jacobi et al. (2016) confirmed this delay with satellite-based EUV-TEC measurements (Unglaub et al., 2011) and also calculated the ~~delay with EVE fluxes, because proxies like F10.7 or EUV-TEC (Unglaub et al., 2011) are not able to cover all ionospheric effects. In addition,~~ ionospheric delay with EUV fluxes. The validation with EVE flux measurements was important because the solar rotation variations of F10.7 and EUV are not synchronized at all times and the calculated ionospheric delay with F10.7 might be greater than the actual delayed

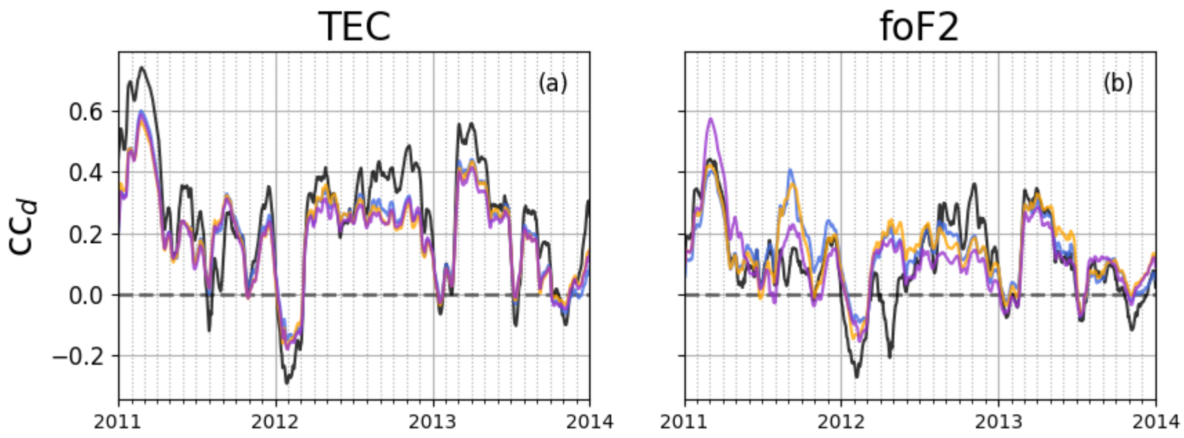

Figure 6. The plots show the correlation coefficients of the ionospheric parameters TEC (a) and foF2 (b) with integrated EVE fluxes (6 to 105 nm) for Tromsø (black), Průhonice (blue), Rome (orange), and Athens (purple). All parameters were analyzed in hourly resolution using a time window of 90 days and a step size of one hour.

ionospheric response to EUV (Woods et al., 2005; Chen et al., 2018). Schmölter et al. (2018) used EVE and GOES EUV fluxes to calculate an ionospheric delay of about 17 hours as mean value based on data at hourly time resolution.

~~We would like to confirm these results and extend the analysis by correlating the integrated EVE fluxes for the whole EUV spectrum (from 6 to 105 nm) with the relevant ionospheric parameters TEC and foF2. Furthermore, we investigate similarities and differences~~ In the calculation of the ionospheric delay~~using data from both hemispheres and provide temporal and regional dependencies. In the calculation~~, a time window of 90 days and a step length of one hour are used for the cross-correlations. This time frame not only allows to produce reliable results for the delay, it also allows to identify changes in the delay over time. The calculation is applied to the time series from December 2010 to February 2014 and covers a time period of roughly three years.

The results for the European stations are shown in Figure 6 for TEC and foF2. The trend of the correlation coefficients of TEC for the four European stations are very similar. The station Tromsø has more significant peaks (for increases and decreases in the correlation), but follows the same general trend. At the end of each year the correlation decreases significantly and reaches negative values~~, which was already seen in Figure 4~~. In Figure 4, this was interpreted as a possible effect of ~~the~~ geomagnetic activity. At the end of the chosen time period~~the correlation gets especially low, which is~~ , the correlation coefficient drops due to data gaps and the applied interpolation ~~.~~method.

The correlation coefficients of foF2 for the four European stations are smaller than ~~for TEC. The results show a similar trend compared to correlation coefficients of TEC and~~ those of the TEC. However, the trends of the two correlation coefficients are similar for the different stations. The correlation coefficients for the station Tromsø ~~show again~~ again show the largest deviation from the mean of the trends of ~~the other~~ all stations. Since Tromsø is an auroral station, the processes in the ionosphere for this location are influenced by other mechanisms, e.g., particle precipitation or thermospheric heating controlled by the solar wind

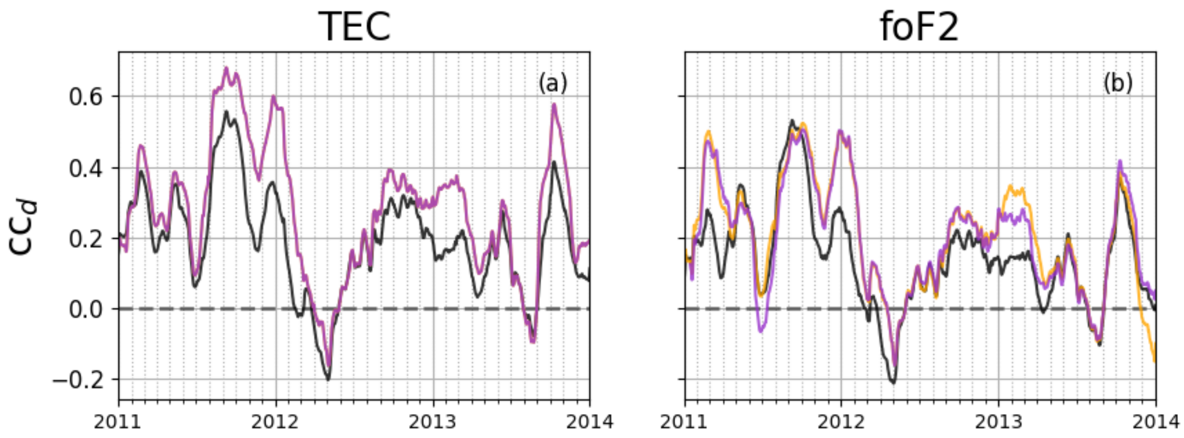

Figure 7. The plots show the correlation coefficients of the ionospheric parameters TEC (a) and foF2 (b) with integrated EVE fluxes (6 to 105 nm) for Darwin (black), Camden (orange), and Canberra (purple). All parameters were analyzed in hourly resolution using a time window of 90 days and a step size of one hour.

(Hunsucker and Hargreaves, 2002). ~~We still include this station~~ The station is still in the analysis of the delayed ionospheric response as the northern boundary for the European region.

The ~~results~~ TEC and foF2 correlation coefficients for the Australian stations ~~for TEC and foF2~~ are shown in Figure 7. In general, the correlation coefficients of TEC and foF2 are slightly larger than for the European stations. The trend of correlation coefficients for both parameters and the trend for the different stations are in good agreement. The suggested impact of the geomagnetic activity is less present in these results~~, and especially~~. Most notably, the decrease and minimum in December 2012 does not occur. The difference might be due to further impacts on the correlation, e.g. thermospheric wind conditions or seasonal variations due to composition changes (atomic/molecular ratio), which are not covered in this study, but ~~which~~ are known to have a strong impact on the ionospheric state (Rishbeth, 1998; Rishbeth et al., 2000).

The results of the delay calculation through cross-correlations are shown in Figure 8 and 9. The trend of the delay for TEC and foF2 at the European stations in Figure 8 is in agreement with the trend found by Schmölter et al. (2018), having a slow increase in the delay during the first half of the year, a maximum of the delay close to the end of the year and a sudden decrease of the delay at the end of the year. This pattern repeats in the three years of the chosen time period. The trend of the delay for TEC and foF2 at the Australian stations in Figure 9 is very similar, but shows a less linear increase of the delay in each year. Contrary to the correlation coefficients in the Figures 6 and 7, the delays show a good correlation with the geomagnetic activity in both hemispheres. Hence, this global trend confirms an additional dependence of the delay on the geomagnetic activity.

The maxima of the delay increase from year to year in 2011 to 2013 (especially for foF2) in the northern hemisphere. A similar trend occurs in the southern hemisphere from 2011 to 2012. This small increase might result from the growing solar activity in the same time period. Figure 10 shows the data for integrated EUV during the analyzed time period and the calculated delay for TEC at Rome and Canberra. As a very coarse visualization for the correlation between EUV and delay, the linear

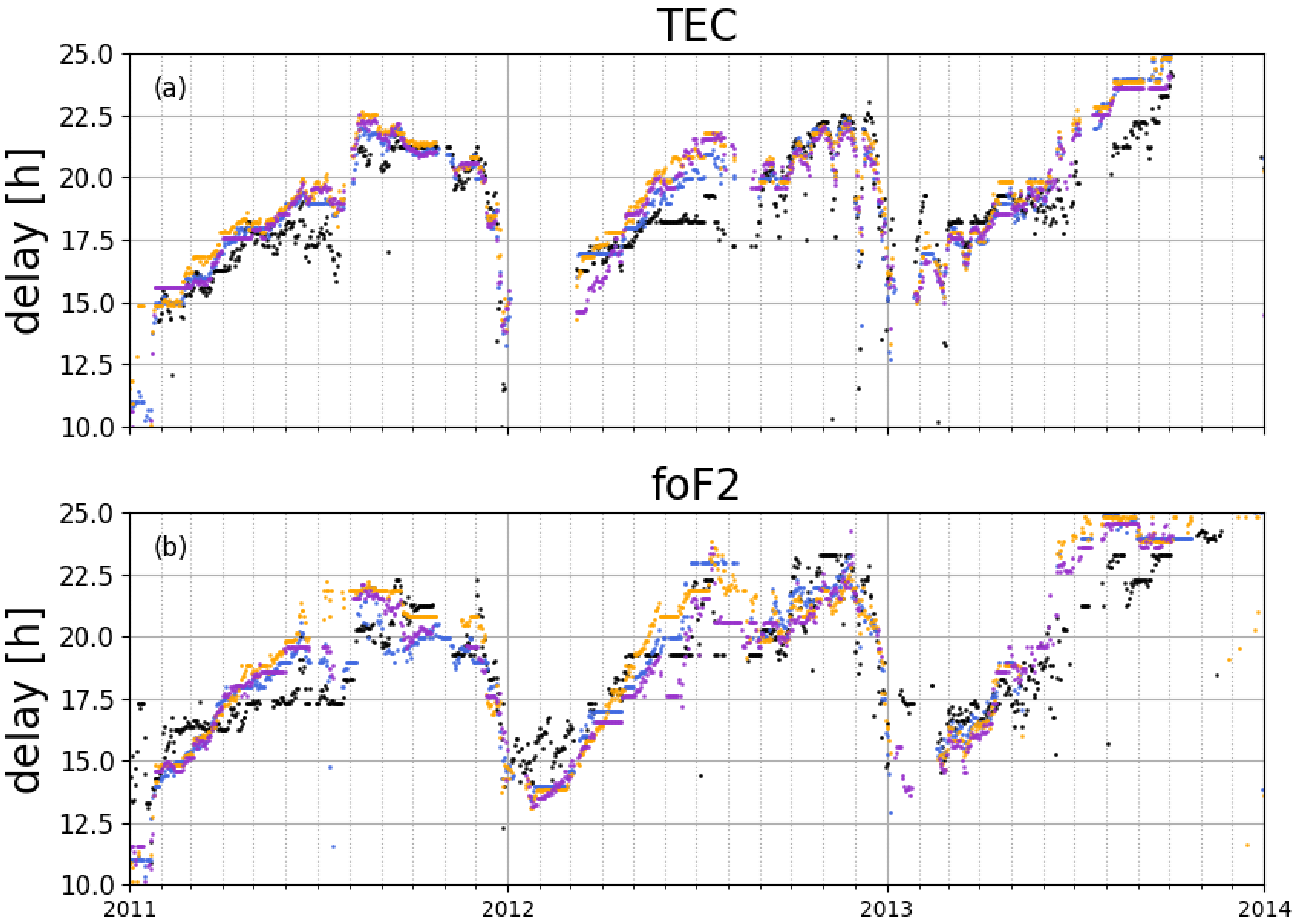

Figure 8. The plots show the delays of the ionospheric parameters TEC (a) and foF2 (b) with integrated EVE fluxes (6 to 105 nm) for Tromsø (black), Průhonice (blue), Rome (orange), and Athens (purple). All parameters were analyzed in hourly resolution using a time window of 90 days and a step size of one hour.

trends in both data sets are shown as well. The long-term trends of EUV and the delay on the northern and southern hemisphere increase within the chosen time period. Thus, during the solar maximum (cycle 24), long-term changes in the EUV seem to correlate with variations in the delay. A similar behavior was suggested by Schmölter et al. (2018) based on an analysis using GOES data for the same time period. Rich et al. (2003) indicated a smaller delay for solar minimum and a longer delay for solar maximum, and Chen et al. (2015) found a decrease in the trend of the delay with decreasing solar activity. Both analyses calculated the delay ~~only in daily resolution but on~~ at a daily resolution for longer time periods than the one used in this study.

~~As seen in Figures 6 and 7, the delays~~ The difference between the ionospheric delay for the European and Australian stations ~~do not show an obvious difference with respect to seasonal variations~~ in Figures 6 and 7 show only small differences due to

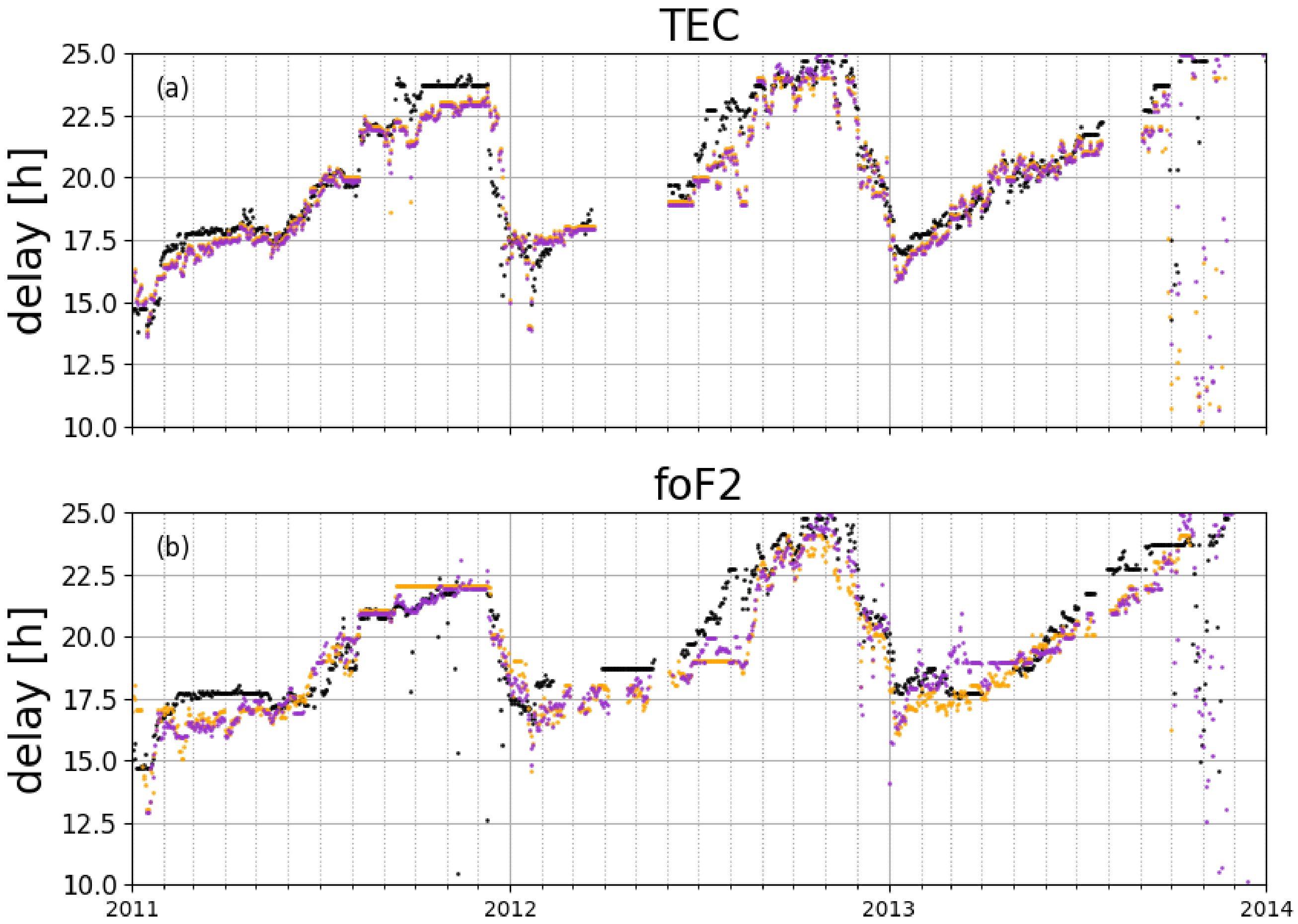

Figure 9. The plots show the delays of the ionospheric parameters TEC (a) and foF2 (b) with integrated EVE fluxes (6 to 105 nm) for Darwin (black), Camden (orange), and Canberra (purple). All parameters were analyzed in hourly resolution using a time window of 90 days and a step size of one hour.

the ~~global trend , which~~ assumed trend with the geomagnetic activity. This trend has to be removed in the further analysis. Therefore, ~~we picked~~ the European station Rome with a latitude of ~~$\approx 42^\circ$~~ 41.8°N (geomagnetic latitude ~~$\approx 42^\circ$~~ 41.8°N) and the Australian station Canberra with a latitude of ~~$\approx 35^\circ$~~ 35.3°S (geomagnetic latitude ~~$\approx 43^\circ$S)~~ 42.3°S) are used for the comparison of the northern and southern hemispheres. ~~In our analysis we indirectly eliminated the global trend~~ The non-seasonal trends are removed by calculating the difference between the ~~delays calculated at~~ ionospheric delays of both stations. The results are shown in Figure 11. The difference between both stations clearly shows a seasonal variation in the northern and southern hemisphere with a greater delay for Rome in the northern hemisphere summer and a greater delay for Canberra in the southern hemisphere summer. The delay difference varies over different ranges for the parameters: TEC with $\approx 5 \pm 0.7$ hours and foF2

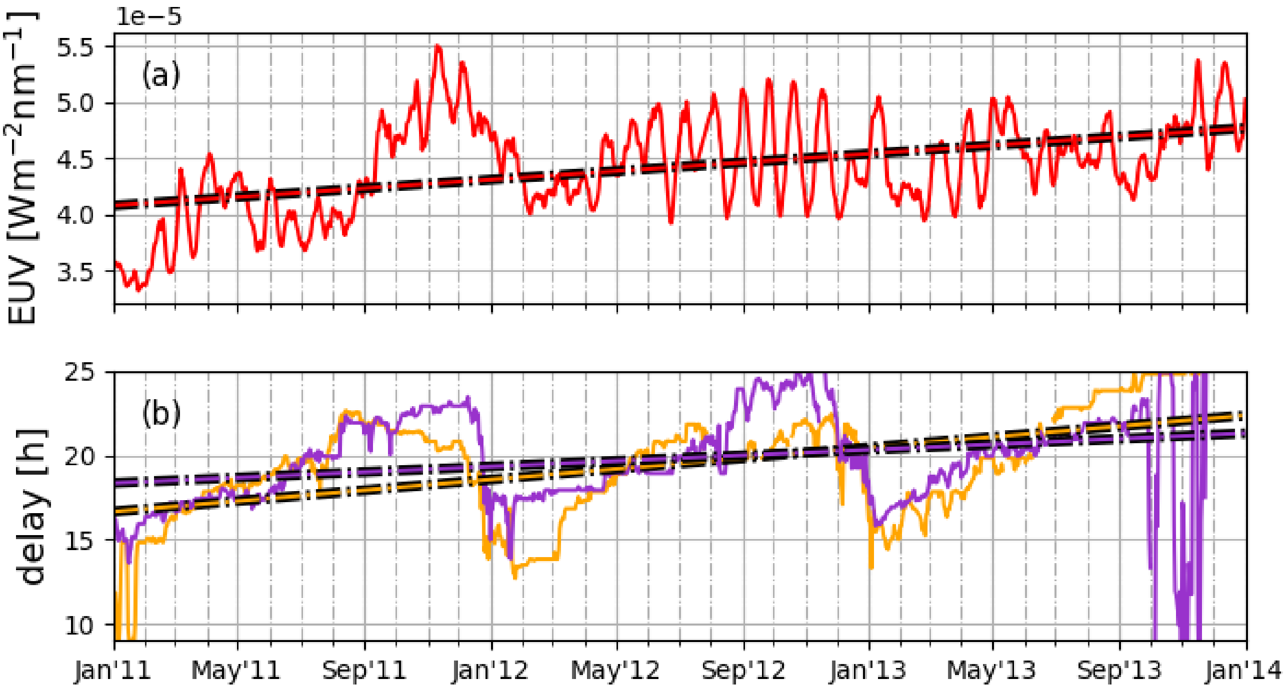

Figure 10. Plot (a) shows the the integrated EUV fluxes from 6 to 105 nm and the linear trend of the EUV (dash-dotted line). Plot (b) shows the delays of TEC against EUV for Rome (orange) and Canberra (purple), as well as the linear trends of the delays (dash-dotted lines).

with $\approx 8 \pm 0.8$ hours. These results ~~indicate a strong~~ could indicate a stronger seasonal variation of the ionospheric delay in the F2 layer compared to the whole ionosphere-plasmasphere system~~.~~, but there are other possible sources for the difference (e.g. the background model of the IGS TEC maps). Similar to the discussion of the impact of diurnal variations, such findings need to be confirmed with modeling efforts. In conclusion, the trends of the ionospheric delay for TEC and foF2 are very similar and both ionospheric parameters show features of the seasonal variations.

5 Analysis of the delay for mid-latitudes

Another trend visible in Figure 8 is a decrease of the delay with latitude in summer. The station at Tromsø shows the shortest delay of the European stations for both parameters. The differences in the delay between Průhonice, Rome, and Athens are smaller. ~~The different delay between~~ Figure 12 shows the difference between the stations Rome and Tromsø for both ionospheric parameters. The results for TEC show a greater or similar ionospheric delay for the station Rome compared to the station Tromsø~~and the other European stations is expected due to the explained differences in the auroral region. The latitudinal dependence is not visible during winter.~~. There are only a few short time periods during winter with a greater ionospheric delay for the station Tromsø. A stronger seasonal variation appears for the parameter foF2, but overall the ionospheric delay is still

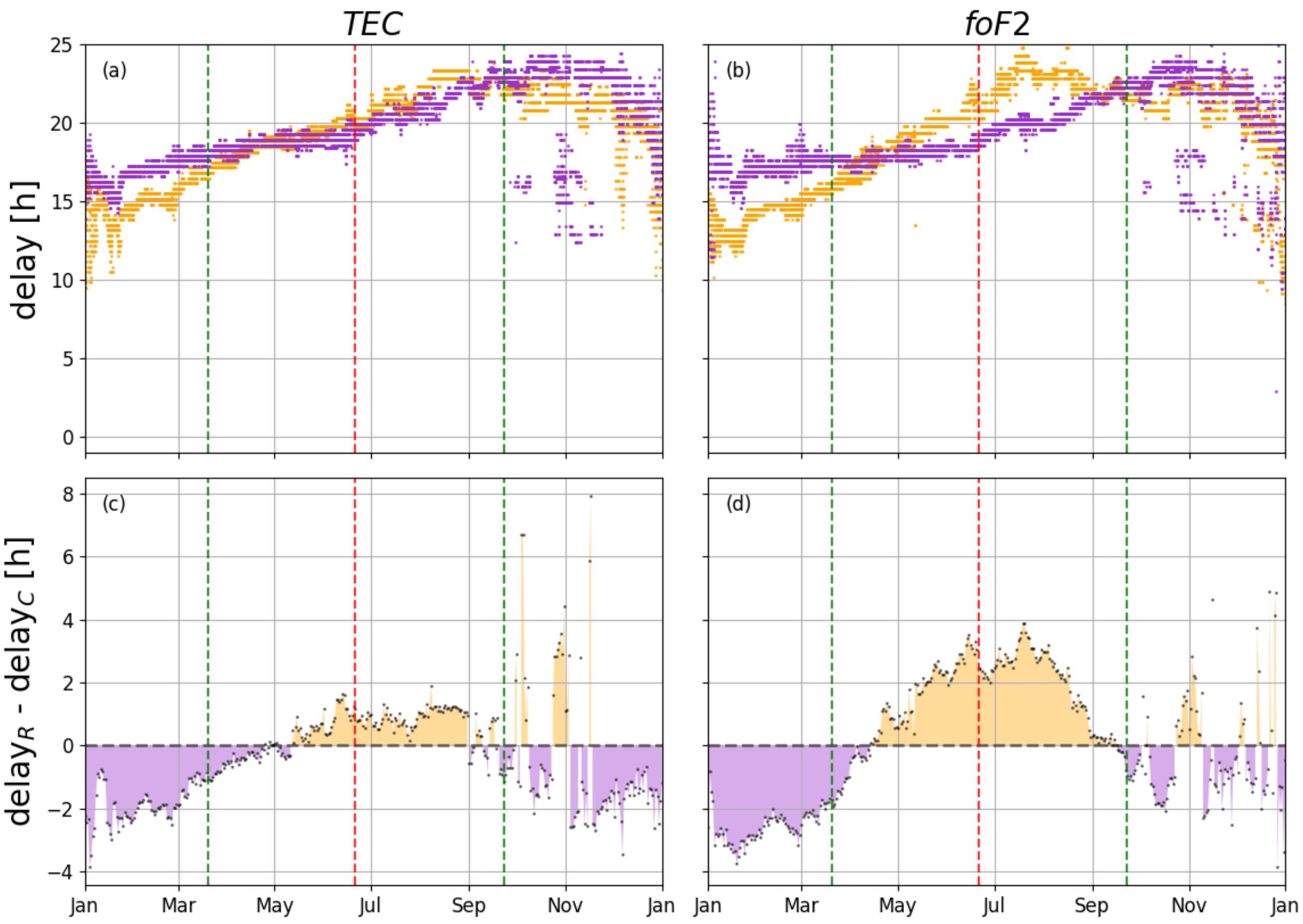

Figure 11. Superposed epoch plots for the delay (a, b) and difference in delays (c, d) for the ionospheric parameters TEC and foF2 with integrated EVE fluxes (6 to 105 nm) for Rome (orange) and Canberra (purple). The temporal resolution is one hour. Equinoxes are marked with the green dashed lines and solstice is marked with the red dashed line.

greater for the station Rome. The mean difference for results in Figure 12 is $\approx$ 1.08 hours for TEC and $\approx$ 0.52 hours for foF2. The changes with latitudinal dependence of the trends during winter are due to the stronger increase of the ionospheric delay for Rome during summer. No such trend is visible for the Australian stations and there are only minimal differences in the delay. This is probably due to the smaller range of latitudes covered by this stations~~, where data from high-latitudes are missing~~. A precise interpretation of the trend without data from different latitudes in the southern hemisphere is difficult. Nonetheless, the results for the latitudes over Europe ~~agree~~ are consistent with the expectations that different and more varying delays can be observed in polar regions due to the direct impact of the solar wind (Watson et al., 2016) as well as for the equatorial region due to the strong dynamics ~~between the different ionospheric layers~~in ionosphere and thermosphere (Maruyama, 2003).

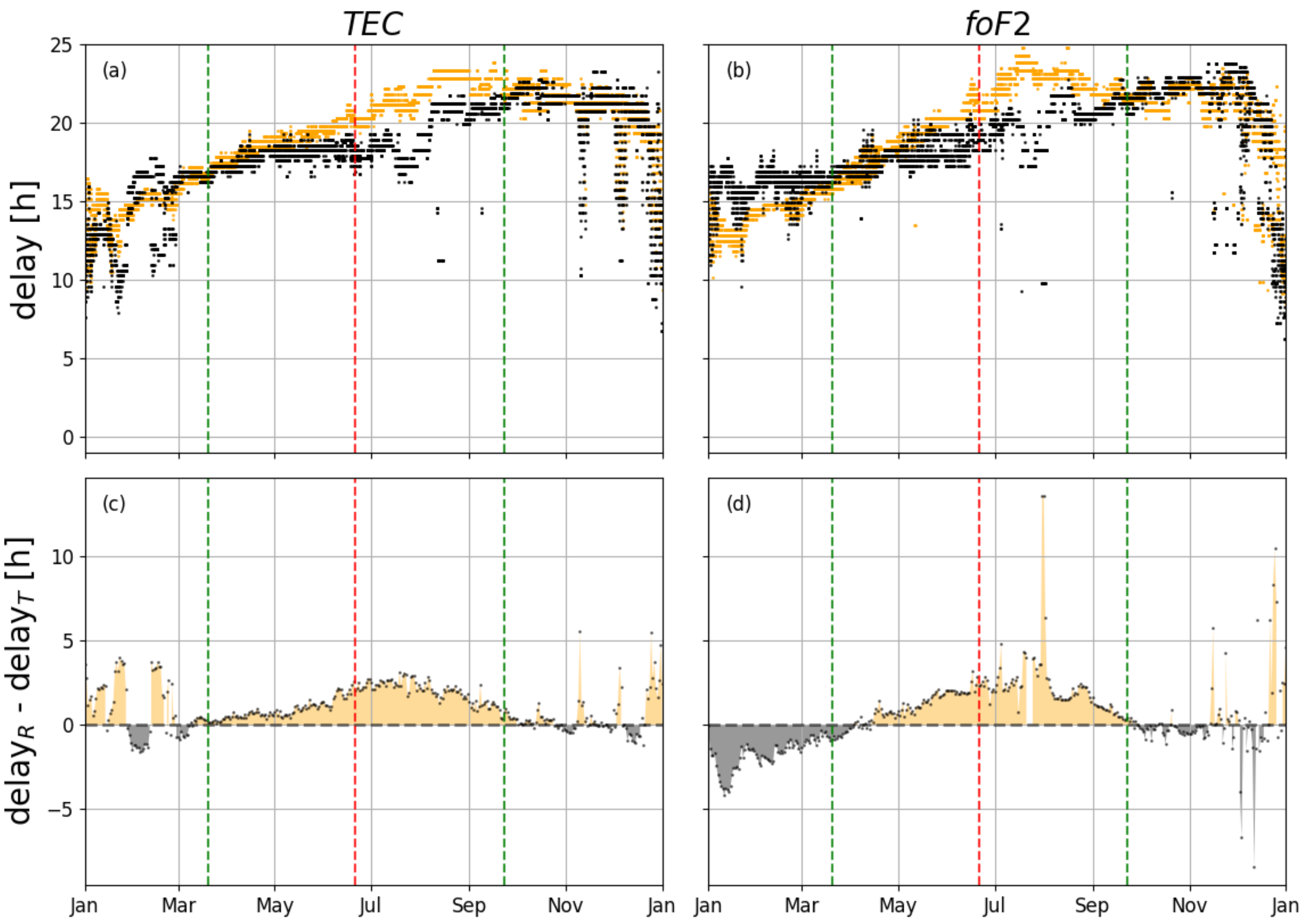

Figure 12. Superposed epoch plots for the delay (a, b) and difference in delays (c, d) for the ionospheric parameters TEC and foF2 with integrated EVE fluxes (6 to 105 nm) for Rome (orange) and Tromsø (black). The temporal resolution is one hour. Equinoxes are marked with the green dashed lines and solstice is marked with the red dashed line.

A further analysis of the mid-latitude delay is possible using TEC data over Europe, where ~~we have good observation~~ a good observational coverage from GNSS stations and only minimal influence by the ionospheric model ~~(for the chosen IGS TEC maps by UPC: a global voxel-defined 2-layer tomographic model solved with Kalman filter and spline interpolation)~~is expected. Therefore, ~~we are able to extract a~~ the region from the TEC maps (30°N to 70°N and 10°W to 30°E) ~~and calculate~~ can be extracted and the time series of the delay for each available grid point can be calculated. This was done by cross-correlations with a time window of 90 days and a step length of one hour ~~. For the results~~ in Figure 13, which ~~shows a map of~~ maps the mean delay values for the mid-latitudes in summer ~~and winter, the mean and standard deviation from May to August and from November to February were calculated~~(May-August) and winter (November-February). ~~The maps in Figure 13 show that the delay is~~ Figure 13 shows ionospheric delays that are consistent with the results from the European ionosonde stations in Figure

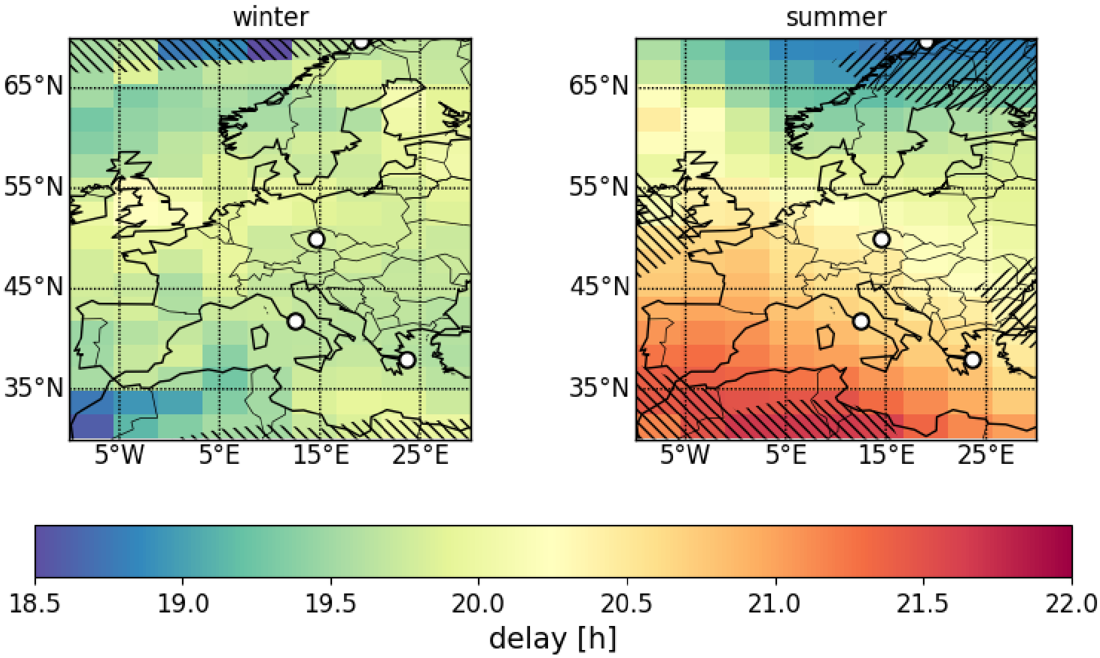

Figure 13. Map of the delay of TEC with respect to EUV in summer (May to August) and winter (November to February) within the time period from January 2011 to ~~2014.~~ December 2013. The delay varies between ≈ 18.6 and ≈ 21.7 hours. The hatched regions on the map represent significantly greater (upper left to lower right fill) or smaller (upper right to lower left fill) correlations compared to the average of each map (± one standard deviation). The absolute correlation coefficient is ≈ 0.28 in summer and ≈ 0.17 in winter. The ionosonde stations Tromsø, Průhonice, Rome and Athens are marked with the white dots.

8. In winter, there is no strong increase or decrease with latitude, but roughly the same delay of ≈ 19.5 hours ~~for the whole region. A slight decrease at the northern and southern boundary support the statement, that the delay is decreasing at polar and equatorial regions~~over the entire region. The decrease of the ionospheric delay at latitudes greater than 65°N and smaller 35°N confirms a latitudinal trend, which was found in preceding studies (Lee et al., 2012). A similar behavior of the delay has been found by Ren et al. (2018). In summer, the delay decreases with ~~latitude from~~ increasing latitude. From ≈ 21.5 hours at 30°N to ~~≈ 19~~ ≈ 19.0 hours at 70°N~~. The gradient in summer describes a change of~~, or ≈ -0.06 hours per degree in latitude. Therefore, the delay maps confirm the latitudinal variations as seen in ~~Figure 8~~ Figures 8 and 12. The variation in delay with longitude is small and does not show any dominant trend in winter. The variation of the delay with longitude in summer is much smaller than ~~in latitude~~ the variation in latitude for the same season, with a change of ≈ -0.01 hours per degree in longitude. The small and similar magnetic declination for the European region could be related to the small variations of the ionospheric delay with longitude. There is an influence of the magnetic declination on the mid-latitude ionosphere, which leads to similar

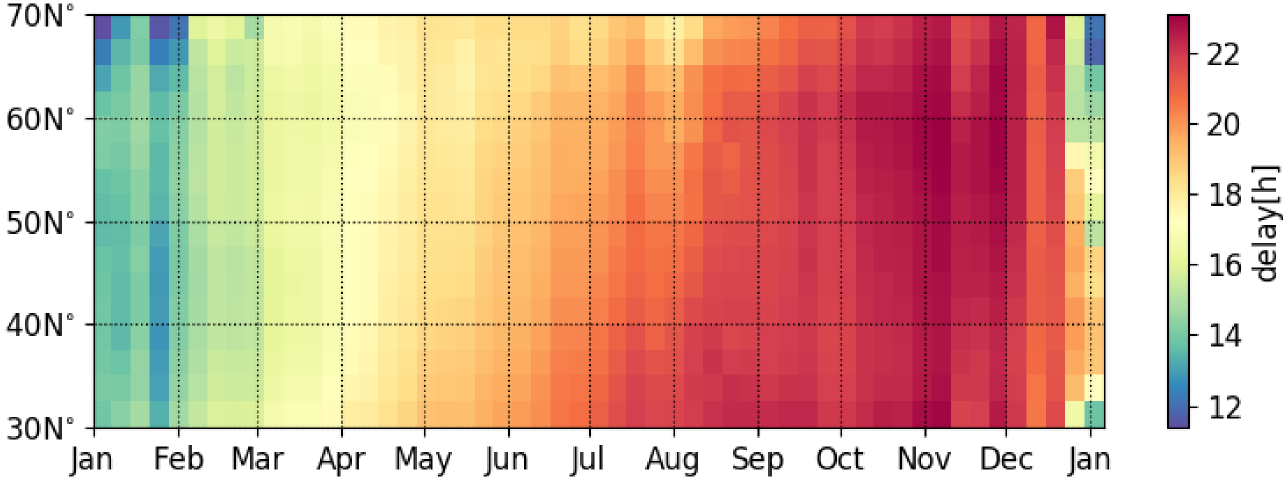

Figure 14. Time series of the delay of TEC with respect to EUV as an epoch plot for the mid-latitudes covering Europe within the time period from January 2011 to December 2013. The delay varies between ≈ 11.3 and ≈ 23.1 hours. The absolute correlation coefficient is ≈ 0.21 during the period.

longitudinal transport processes in all seasons (Zhang et al., 2012, 2013). This behavior has to be explored with observational data for different regions or modeling efforts in the future.

For the further analysis the calculated time series of delay maps is averaged over longitude to get a mean value for the delay at each latitude. The results are summarized with epoch plots in Figure 14 having a ~~resampled~~ resolution of one week ~~to allow~~ (mean value) to allow a better presentation of the long-term changes of the ionospheric delay. The latitude-dependent time series in Figure 14 is consistent with the results and the assumed trend from the seasonal variations is present. In October, the delay reaches the same value for all latitudes and does not change any more until the sudden decrease in December, which happens for all latitudes. ~~A global~~ The trend based on the geomagnetic activity ~~is as well~~ (see Figures 4 and 5) is also represented in Figure 14.

6 Conclusions

The main challenge of delay calculation in high temporal resolution is the impact of the diurnal variations of ionospheric parameters. These have a impact on the calculated correlations coefficients, but do not influence the relative trend in a significant way. ~~We~~ This study proved that a reliable delay calculation is possible on hourly resolution by different analysis: comparison of delays between fixed local time and fixed location as well as comparison of correlation coefficients on different time scales. These results are important for future analysis of the delay in high temporal resolution.

~~In our main analysis we~~ The main analysis confirmed the findings of previous studies dealing with variations of the delayed ionospheric response to solar EUV with solar activity and latitude~~.~~:

- The geomagnetic activity has a strong influence on the delay, which is visible as global trend in the delay within this study. The strong impact of the geomagnetic activity was already suggested in other studies, e.g. Ren et al. (2018).
- The results indicate an influence of the 11-year solar cycle or at least an increase of the delay with increasing solar activity from year to year. This result is consistent with findings by Rich et al. (2003) and Chen et al. (2015).

The variability of the delayed ionospheric response to solar EUV with geomagnetic activity and the seasonal variations of the delay was shown with delay time series from January 2011 to December 2013. These findings allow the following conclusions:

- The comparison of the delay for locations in northern and southern hemisphere shows a seasonal variation, which occurs for both investigated ionospheric parameters TEC and foF2. The seasonal variation for foF2, which describes only the F2 layer, is larger compared with TEC of the whole ionosphere-plasmasphere system.
- The analysis of IGS TEC maps covering the European region indicates a latitudinal dependence of the delay for mid-latitudes, which is pronounced in summer and vanishes in winter. A North-South trend of the ionospheric delay during summer month has been observed with ≈ 0.06 hours per degree in latitude.
- ~~The geomagnetic activity has a strong influence on the delay, which is visible as global trend in the delay within this study. The strong impact of the geomagnetic activity was already suggested in other studies, e.g. Ren et al. (2018).~~
- ~~The results indicate an influence of the 11-year solar cycle or at least an increase of the delay with increasing solar activity from year to year. This result is consistent with findings by Rich et al. (2003) and Chen et al. (2015).~~

For the seasonal variation the difference in the delay was calculated at stations of similar latitude in both hemispheres for TEC with $\approx 5 \pm 0.7$ hours and foF2 with $\approx 8 \pm 0.8$ hours. The decrease of the delay with latitude in the European mid-latitudes from ≈ 21.5 hours at $30°$N to ≈ 19 hours at $70°$N in summer and the roughly constant delay of ≈ 19.5 hours for the whole region in winter also show a seasonal difference in the delay.

~~In future analysis the delay should be calculated for even~~ Future analysis would benefit from high resolution ionospheric delay calculations for longer time periods ~~in high temporal resolution covering~~ that cover different solar and geomagnetic activity conditions. This requires better and more EUV measurements though. ~~In addition, the analysis of the influence of thermospheric conditions is important~~The thermospheric conditions (e.g. neutral winds or composition changes in the atomic/molecular ratio), which are known for their impact on the ionosphere (Rishbeth, 1998; Rishbeth et al., 2000) should be included in future analysis as well. Results presented need to be further confirmed and studied by model calculations. The underlying processes for the delayed ionospheric response to solar EUV radiation need to be described, since this knowledge is an opportunity to validate or improve physics-based models.

Data availability. Kp-index data have been provided by NASA through https://omniweb.gsfc.nasa.gov/form/dx1.html.

IGS TEC maps have been provided by NASA through ftp://cddis.gsfc.nasa.gov/gnss/products/ionex.

Ionosonde data have been provided by NOAA ftp://ftp.ngdc.noaa.gov/ionosonde/. SDO-EVE data have been provided by Laboratory for Atmospheric and Space Physics (LASP) through http://lasp.colorado.edu/eve/data_access/evewebdata.

The shapefiles of the World Magnetic Model have been provided by NASA through ftp://ftp.ngdc.noaa.gov/geomag/wmm/wmm2015/shapefiles/.

The International Geomagnetic Reference Field has been provided by NASA through https://www.ngdc.noaa.gov/IAGA/vmod/igrf.html.

Author contributions. E. Schmölter performed the calculations and composed the fist draft of the paper. J. Berdermann, N. Jakowski, and Ch. Jacobi actively contributed to the analysis and paper writing.

Competing interests. Ch. Jacobi is one of the editors-in-chief of Annales Geophysicae.

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