Response to Anonymous Reviewer #1

Authors' response to Reviewer #1 comments on "Evaluation of the uncertainty of the spectral UV irradiance measured by double- and single-monochromator Brewer spectrophotometers". The authors thank the Reviewer for the additional revision of the manuscript as well as for their suggestions for improving the clarity of the text and reply to all comments below.

The answer is structured as follows: (1) comments from Reviewer #1, (2) authors' response and (3) authors' change in the manuscript.

(1) Line numbers refer to the version with tracked changes

(1) 101: Replace the text in parentheses with "such as stray light and wavelength alignment". I suggest removing "wavelength accuracy" as it is related to alignment.

(2, 3) Following the reviewer's comment, the term "wavelength accuracy" has been removed from the manuscript and the text in parentheses has been replaced with "such as stray light and wavelength alignment".

(1) 119: Keep only the word "iris" and remove "diaphragm".

(2, 3) Done.

(1) 124: Replace "spectrometer" with "spectrometer's entrance slit".

(2, 3) Done.

(1) 155: Replace "at zenith" with "towards the UVB port"

(2, 3) Done.

(1) 212: I suggest rephrasing "uncertainty values have been given" to "typical uncertainty estimates have been assumed"

(2, 3) Done.

(1) 226: Replace "are" with "is"

(2, 3) Done.

(1) 275: Replace "in total" with "on average", since you say "by each Brewer"

(2, 3) The term "in total" has been replaced with "on average".

(1) 324: Replace "metalling" with "metal"

(2, 3) Done.

(1) 420: Replace "those Brewer" with

(2, 3) The reviewer's sentence is incomplete. Maybe they were referring to the typo found in the term "those Brewer". Therefore, the previous term has been replaced with "those Brewers", in plural.

(1) 455: I suggest removing this sentence because the state of the atmosphere has nothing to do with the performance of the instrument. The reason stated in the previous sentence for using only spectra at SZA<90 is sufficient.

(2, 3) Following the reviewer’s comment, the indicated line has been removed from the manuscript.

(1) 839: Replace "exploit" with "represent"

(2, 3) Done.

Response to Anonymous Reviewer #3

Authors' response to Reviewer #3 comments on "Evaluation of the uncertainty of the spectral UV irradiance measured by double- and single-monochromator Brewer spectrophotometers". The authors thank the Reviewer for the additional revision of the manuscript and reply to all comments below.

The answer is structured as follows: (1) comments from Reviewer #3, (2) authors' response and (3) authors' change in the manuscript.

(1) SPECIFIC COMMENTS

(1) 1. Brewers with incomplete characterisation: I remain convinced that Brewers with incomplete characterisation (e.g., lacking temperature and angular characterisation) should not be included in this study. These are known sources of error, and it is well established that neglecting them leads to inconsistent results. Is it truly useful to demonstrate that, when important error sources are not accounted for, the uncertainty estimation is inaccurate and the comparison to reference instruments does not yield a ratio close to 1?

(2) We agree with the reviewer that it would be nice that Brewers were completely characterised, however, this is not the actual situation, without standard protocols for measuring their angular response and with most of the Brewers in the world lacking both temperature and angular characterisation. Even within the European Brewer Network (EuBrewNet), which leads some improvements in Brewer's measurement, only a few Brewers have their cosine response measured, and the temperature correction is lacking in almost all of them. In our particular case of the 18th Brewer Regional Brewer Calibration Center for Europe (RBCC-E) Intercomparison, five among the sixteen participating Brewers had their cosine response measured and only one also the temperature correction. Although the cosine correction and temperature effect were known as sources of uncertainty, only recently their importance has been acknowledged and efforts to correct them are being made by the Brewer community.

In this framework, the present study uses a thorough Monte Carlo method to provide a reliable quantification of the combined uncertainty derived from several important sources of uncertainty, acknowledging the lack of the contribution of the cosine correction and temperature in some of them.

On the other hand, the inclusion in the study of those five non completely corrected Brewers is also useful in terms of comparison with respect to the fully-corrected Brewers, showing the uncertainty due to only certain sources. Additionally, they show values that, though underestimated, represent the incomplete combined uncertainty that can be calculated for the great majority of the Brewers in the world.

For all this, we believe that the study is more complete and informative including the complete set of ten Brewers participating in the European intercomparison campaign.

(1) 2. Angular corrections: The authors state that "the results show that including the cosine correction improves considerably the comparison to the QASUME". However, this is not demonstrated in the present paper. To support this claim, the ratios to QASUME should be shown with and without the angular correction for the same instruments. Instead, Figures 4a and 4b present different groups of instruments, which prevents a direct comparison.

(2) As the reviewer states, the referred claim is not demonstrated in the present paper (it is not our aim nor focus), but it is rather a result of the report elaborated by PMOD/WRC (Hülsen, 2023) and the study of López-Solano et al. (2024). Therefore, the references have been added and the sentence has been rewritten searching for more clarity.

(3) For greater clarity, lines 498–499 have been modified to "The results reported by López-Solano et al. (2024) showed that including the cosine correction improves considerably the comparison to the QASUME, in agreement with the findings of Hülsen (2023).

(1) Additionally:

- (1) A discussion of the steps recommended by EUBREWNET to better characterise the angular response of Brewers lacking such data would be useful

(2) EuBrewNet provides no guidelines on how to measure correctly nor suggestions on how to improve the angular characterisation of the instrument. Its role in the RBCC-E campaigns is limited to the processing of the UV irradiance measured by the participating Brewer spectrophotometers. Although it recognizes the improvement in the calibration if the Brewer is corrected from its cosine response, this characterisation is not performed routinely. In order to fulfil this demand, the UEx-INTA research group has developed a specific device to operatively measure the angular response of Brewers in campaigns. This device is being applied to some Brewers and their measured angular responses are being included in the calibration procedure, but its use is not yet general.

(3) To avoid confusion, the manuscript has been revised to remove any reference to "guidelines" or "protocols" regarding EuBrewNet. Now, only the processing algorithms are mentioned throughout the manuscript.

- (1) How much do angular responses vary among different Brewers? As a first approximation, what would be the expected error in applying an "average" angular response to uncharacterised Brewers?

(2) The UEx-INTA research group is studying the angular correction of the Brewer spectrophotometer, its variability among Brewers, etc However, this topic, though being interesting, is outside the scope of this study, which focuses on obtaining the global uncertainty of Brewer's measurement in its operation state as a combination of the uncertainty due to different sources, being the cosine response one of them.

(1) 3. Brewer stability: As noted in line 296, "the responsivity of the instrument varies with time". Accordingly, should this source of uncertainty be expressed as a percentage per month or per year, depending strongly on the calibration schedule followed by the operator? What are the EUBREWNET recommendations regarding calibration frequency? Are Brewers calibrated only every two years considered "compliant" with EUBREWNET protocols?

(2) As the reviewer states, the responsivity of Brewers changes with time. At 320 $\pm$ 5 nm, we found a steady decrease of around 2.8 % and 2.2 % per year for Brewers #150 and #185, respectively. As for Eubrewnet, it does not have any rules about calibration frequency for UV measurements (it is the PI of the instrument who decides). There is a recommendation for ozone calibration: two years for network instruments and one year for NDACC and reference instruments. As mentioned earlier, there are no protocols in EuBrewNet yet. As a result, the calibration frequency depends on the Brewer.

(3) Following the reviewer's comment, the following information has been added in line 298: "For Brewers #150 and #185 their responsivity at 320 ± 5 nm decreased at a rate of 2.8 % and 2.2 % per year, respectively".

(1) 4. Brewer operation: In my view, the study shows that some instruments are not operated correctly, making it questionable to characterise their uncertainty. For instance, there are Brewers that are "not calibrated frequently enough" (line 303) or use obsolete dispersion functions. Do the authors truly wish to include such instruments in their uncertainty assessment? Are they genuinely representative of the uncertainty associated with UV irradiance measurements? For example, wavelength shifts of 0.1 nm (line 706) are not acceptable. Therefore, instead of, or in addition to, recommending that each Brewer be individually characterised, the authors should emphasise that Brewers must be operated as intended, following proper procedures and calibration schedules.

(2) Measuring spectral UV irradiance is a demanding task, with stringent QA and QC protocols. In fact, fulfilling all the requirements that entail a high standard QC is beyond the facilities or abilities of most operators (Webb et al., 1998; Bernhard and Seckmeyer, 1999). As a result, it was to be expected that several Brewer spectrophotometers do not meet these high standards. Nevertheless, as Webb et al. (1998) states, this should be viewed as encouraging goals that help improve the quality of the data.

As for wavelength shifts, wavelength shifts of 0.1 nm are not unusual. Several UV spectroradiometers (Bentham DTMc300 spectroradiometer, Dilor XY spectrometer, as well as Brewer MkIII and MkII spectrophotometers) have reported shifts of this order (Bais et al., 2001; Garane et al., 2006). Regarding calibration frequency, typical uncertainty values have been assumed, following the findings of Garane et al. (2006), Lakkala et al. (2008), and González et al. (2023).

Furthermore, the uncertainty estimates found in this study are similar to the ones found in other Brewer spectrophotometers and UV spectroradiometers (see Section 6).

For these reasons, we believe that the uncertainties reported in this work are representative of the uncertainty in UV irradiance. However, we agree with the reviewer that these uncertainty sources (radiometric stability and wavelength misalignment), along with the limitations found in the characterisation of the instruments, show that Brewer spectrophotometers need QC protocols (as stated in Section 6) as well as procedures to ensure the proper operation of the instrument (the manuscript currently lacks this information).

(3) To emphasise the proper operation of Brewer spectrophotometers, the following information has been added In line 720: "This shows the importance of the maintenance of the instrument. Brewer spectrophotometers must be operated following stringent procedures and calibration schedules".

(1) 5. Wavelength choice for some plots: The selection of 335 nm for some plots (e.g., Figure 3) is rather unconventional. A key motivation for UV irradiance measurements is the analysis of the effects of ozone variability or biological impacts (lines 662–664). As such, evaluating uncertainty at UV-B wavelengths, where ozone absorption is also stronger, would be more informative. Furthermore, some Brewers do not measure at wavelengths above 325 nm, further questioning the relevance of 335 nm as a representative choice.

(2) The wavelength 335 nm was chosen to minimise the effect of the fluctuations found for some of the Brewers studied. However, we agree with the reviewer that analysing a shorter wavelength can be more interesting.

(3) Following the reviewer's comment, all figures were revised, finding that the selected wavelengths for Figures 3 and 7 (335 and 350 nm, respectively) were not representative. Therefore, the selected wavelength for the previous figures has been updated to 305 nm, a wavelength that can be used to analyse ozone variability and biological effects. This has resulted in the following figures and captions:

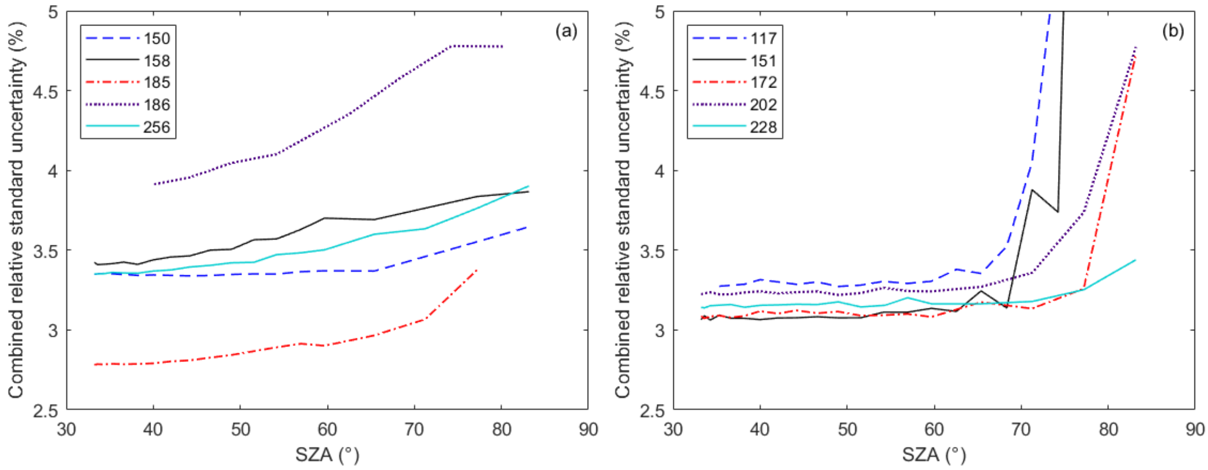

Figure 3. Relative combined standard uncertainties of all UV irradiances measured on 13 September 2023 at 305 nm. (a) First group (double Brewers with cosine correction). (b) Second group (two single and three double Brewers with no cosine correction implemented).

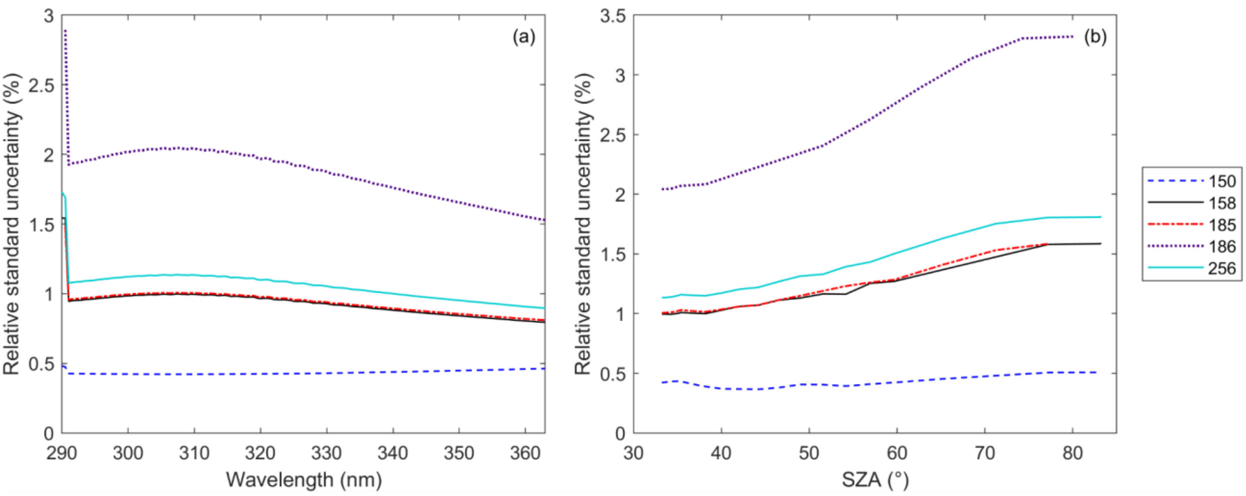

Figure 7. Relative standard relative uncertainty on 13 September 2023 caused by the cosine correction implemented. (a) Spectral dependency at 12:30 UTC. (b) SZA dependency at 305 nm.

(1) 6. SZA dependence of the uncertainty: The results in Figure 3b, indicating that the relative uncertainty does not vary with solar zenith angle (SZA), are highly suspicious. At least, measurement noise and wavelength misalignments, particularly at shorter wavelengths, should result in increased uncertainty at higher SZAs, as also acknowledged in lines 527–529. Stray light should also play a more significant role under these conditions, and the uncertainty associated with its correction is expected to increase, as stated in lines 569–570. In my opinion, the key limitation of Fig. 3 is that the choice of 335 nm does not reflect the most critical effects. This also leads to the possibly wrong conclusion that "For half of the Brewers studied, the relative uncertainty shows no spectral nor angular dependency", as the behaviour at shorter wavelengths could differ substantially.

(2) Indeed, all the mentioned uncertainty sources cause the relative combined standard uncertainty to increase with SZA at shorter wavelengths. At larger wavelengths, their impact is reduced and the relative uncertainty levels off. Nevertheless, we agree with the reviewer that shorter wavelengths can be more interesting as they are important for ozone and biological studies.

(3) Following the reviewer's comment, Figure 3 has been updated to show the relative combined standard uncertainty at 305 nm (see the previous response). The discussion regarding this figure (lines 486–490) has been changed to "Regarding the angular dependency, Figure 3 represents all the relative uncertainty values derived on 13 September at 305 nm. This wavelength was selected as its analysis is interesting for studying ozone variability and biological effects. Figure 3 shows that the relative combined standard uncertainty of the Brewers studied increases with SZA at short wavelengths. This increase is especially marked for single Brewers, due to the uncertainty in stray light correction". Furthermore, Section 6 has also been revised to remove any wrong conclusions. As a result, lines 700–705 have been modified to "For the Brewers studied, the relative uncertainty increases with SZA at short wavelengths. This behaviour is linked to wavelength shifts, noise, and the correction of stray light, cosine error, and dark counts".

(1) 7. Clear-sky conditions: It should be clearly stated throughout the paper that this uncertainty assessment applies only under clear-sky conditions.

(2, 3) The conditions in which the UV measurements were performed have been added in the introduction and conclusions section. They have also been discussed at the beginning of the methodology section and in greater detail in Section 3.1.3. Furthermore, they were also stated in the results section following the comments made by Reviewers #1 and #3 in the first round of revision.

(1) 8. Section 5: This section still appears unnecessary and rather forced. Some of its content could be incorporated into the Introduction as the rationale of the study, while the remainder could be moved to the Conclusions. Removing this section entirely would improve the overall structure and flow of the paper.

(2) Section 5 plays a key role in justifying the relevance of this work for publication in ACP, as it is necessary to highlight the importance of Brewer uncertainty evaluation. However, we agree with the reviewer that the section can be revised and enhanced to better align with the overall flow of the paper.

(3) Following the reviewer's comment, Section 5 has been revised to improve its clarity and relevance, as follows:

"In the previous section, the combined standard uncertainty and the main sources of uncertainty of single and double Brewer spectrophotometers have been determined. These aspects are of great interest for identifying the type of studies for which Brewers are most suitable, given that the required uncertainty in global UV irradiance measurements depends on the intended use of the data.

One of the key applications of spectral UV measurements is the computation of effective irradiance for various biological effects, such as erythema, vitamin D synthesis, melanoma risk, and DNA damage, through the integration of the spectral irradiance weighted by different action spectra (Webb et al., 2011). The findings benefit regulatory applications, supporting evidence-based UV exposure limits for outdoors workers (Vecchia et al., 2007) and improving standards for sun protection products (Young et al., 2017). For these types of studies, the standard procedure is to use instruments with relative irradiance and erythemal uncertainties of less than 7 % in the UV-B region (e.g. Bilbao and de Migue, 2020; Cede et al., 2002; McKenzie et al., 1991). Therefore, double Brewer spectrophotometers are suitable for biological studies. However, single Brewers might be limited as their relative uncertainty rises rapidly with SZA (see Fig. 3), up to 30 % at 302 nm. This increase is mainly produced by the uncertainty in stray light correction (see Fig. 5 and Table 4), which indicates that the five-wavelength method implemented (described in Section 3.1.1) might need improvement.

Furthermore, spectral UV measurements are also used for the validation of satellite-based UV products from instruments such as OMI, TROPOMI, and TEMPO. In these validation studies, the standard uncertainty of the ground-based instruments used is of the order of 4–10 % (e.g. Klotz et al., 2025; Weish et al., 2008; Zempila et al., 2016). Consequently, the UV data from both MkIV and MkIII Brewer spectrophotometers are reliable for satellite-validation for wavelengths above 305 and 302 nm, respectively.

The more demanding application of spectral UV measurements is trend detection. It requires high-quality and long-term measurements (Bernhard, 2011; Glandorf et al., 2005; Weatherhead et al., 1998) as the trends are expected to be small. For example, between the 1990s and 2010s, long-term trends in UVI, global UV, and erythemal irradiance have typically been a few percent per decade, generally from 2 to 10 % per decade (Bernhard and Stierle, 2020; Bilbao et al., 2011; De Bock et al., 2014; Fitzka et al., 2012; Fountoulakis et al., 2016a, 2018). This indicates that double Brewers are able to detect the current changes in UV irradiance above 305 nm as long as they are properly maintained and their irradiances corrected. On the other hand, single Brewers can also reliably detect these changes at SZAs below 70° and wavelengths above 305 nm.

Finally, an even more ambitious goal is to detect the long-term change in spectral UV irradiance caused by a 1 % change in ozone (Seckmeyer et al., 2001). Bernhard and Seckemyer (1999) calculated that a 1 % change in ozone results in a 4 % change in global UV irradiance at 300 nm (30° SZA and 300 DU). Since the expanded uncertainty ($k = 2$) of the Brewers studied (single and double) ranges from 5.5 % to 7.8 % at 33° and 300 nm, the detection of such a trend might be beyond their capabilities. This holds even if the Brewer spectrophotometer is fully corrected and properly maintained, indicating a substantial reduction of its uncertainty is required (the recommendations for this task are outlined in Section 6). If the trend detection threshold were relaxed from a 1 % to a 3 % change in total ozone, then the instruments studied in the first group (cosine correction implemented) would be able to reliably detect the resulting change in spectral UV irradiance at 300 nm and SZAs below 70°. The remaining Brewers would be able to detect such change at 300 nm for SZAs below 60°".

(1) 9. Emphasis on replacing traditional optics: The paper puts strong emphasis on replacing traditional optics (e.g., lines 32–33 and 723–724). However, I believe the primary message should be to first reprocess existing data, taking angular errors into account. Only after this step, should optical replacement be considered, in order to avoid introducing step changes in the long-term data records. Although this is briefly mentioned in lines 726–728, it is not sufficiently highlighted and does not come across as a key conclusion.

(2) Brewer spectrophotometers with traditional optics have worse angular response while the new optics improve both the response and the overall uncertainty of the instrument. Nevertheless, we agree with the reviewer that such change should not be recommended without first studying the cosine response of the instrument. Moreover, replacing the entrance optics is not an easy task and it could require substantial development and changes in the instrument design (Bais et al., 2005).

(3) Following the reviewer's comment, lines 32–33 and 723–724 have been removed from the manuscript. Furthermore, the discussion carried out in lines 726–728 has been replaced with the following information "Regarding the angular response of the instrument, it should be studied and the existing data reprocessed with the corresponding cosine correction. This correction is necessary to ensure the reliability of the Brewer UV measurements as Brewer spectrophotometers with no cosine correction underestimate the spectral UV irradiance. Furthermore, this study is also essential to accurately determine the overall measurement uncertainty and to guarantee the instrument's suitability for detecting long-term UV trends".

(1) TECHNICAL REMARKS

- (1) Line 21: The phrase "due to the difficulties involved in the uncertainty propagation" is misleading. This study itself demonstrates that the main challenges are from the characterisation of the instrument, not from the propagation of uncertainty. This is also acknowledged at lines 75–76.

(2, 3) Following the reviewer's comment, the phrase "due to difficulties involved in the uncertainty propagation" at line 21 has been replaced with "due to difficulties involved in characterising the instrument".

- (1) Line 30: I still believe that stray light is more closely related to the spectral shape than to the absolute intensity.

(2, 3) Lines 30–31 have been modified to reflect the relationship between stray light and spectral shape as follows: "As the measured wavelength decreases, the correction of dark signal, stray light (for single Brewers), and noise become the dominant sources of uncertainty".

- (1) Line 51: The bibliographic entry for Webb et al., 2003 is missing and should be included in the reference list.

(2, 3) The missing reference has been included in the references section.

- (1) Line 64: There is still no proper reference to protocols concerning UV calibration and measurements within EUBREWNET. Redondas et al., 2018 and Rimmer et al., 2018 focus mainly on ozone measurements. López-Solano et al., 2024 addresses the processing of UV irradiance but does not include protocols or recommendations for measurements or calibrations. The web page https://eubrewnet.aemet.es/dokuwiki/doku.php?id=codes:uvaccess refers instead to UV database access functions and not to formal protocols.

(2) There are no protocols developed for UV or ozone in EuBrewNet. At the moment, only the processing algorithms are available. We are now aware that the manuscript may cause confusion and part of the text needs rephrasing.

(3) The manuscript has been revised to remove any reference to "guidelines" or "protocols" regarding EuBrewNet. Now, only the processing algorithms are mentioned throughout the manuscript.

- (1) Line 115: Please rephrase as: "using a set of filters installed on two wheels".

(2, 3) Done.

- (1) Line 118: Replace "filter wheels" with simply "filters".

(2, 3) Done.

- (1) Line 147: It is unclear what calibration is being referred to here. For global irradiance measurements, the input optics is the UV diffuser, not the zenithal prism.

(2, 3) The calibration mentioned is the one performed for global UV measurements. Following the reviewers' comment, line 147 has been modified to "with the input optics positioned towards the UVB port".

- (1) Lines 203–205 and Sections 3.1.1 / 3.1.3: The distinction between these two categories is not entirely clear. All the sources discussed (wavelength misalignments, temperature dependence, cosine error) affect the raw signal in some way. Perhaps the title of Section 3.1.3 could be revised or expanded to better reflect its specific focus and how it differs from Section 3.1.1.

(2, 3) To further differentiate Sections 3.1.1. and 3.1.3. their titles have been modified to "Uncertainty in Brewer raw signal (counts)" and "Uncertainty in absolute irradiance", respectively.

- (1) Line 214: It would be helpful to specify that the authors are referring to dust particles inside the monochromator, rather than in the atmosphere.

(2, 3) Noted. The term "inside the spectrometer" has been added in line 214 to specify that the dust particles are in the air within the spectrometer and not in the atmosphere.

- (1) Line 286 ("500.0 ± 0.6 mm"): What is the difference between this value and the one reported in line 285?

(2) The value in line 285 is 0.58 mm and the one in line 286 is 0.59 mm.

(3) To avoid confusion, two decimals have been used to express the uncertainty in the distance adjustment. As a result, line 286 has been corrected to "(500.00 ± 0.59) mm" and line 285 to "(500.00 ± 0.58) mm"

- (1) Lines 329–332: The issue discussed in this paragraph appears to concern accuracy, not precision. Please reformulate accordingly to avoid confusion.

(2) The issue discussed in the indicated lines is related to the smallest wavelength increment that the micrometre that rotates the grating can perform. Therefore, "precision" is not the best term to describe it, but "resolution".

(3) The phrase "This precision" in line 330 has been replaced with "This resolution (smallest wavelength increment)". Furthermore, in line 329, the term "precision" has been replaced with "resolution", as well.

- (1) Line 336: This statement applies only to the temperature dependence in global UV measurements. Please make this limitation explicit.

(2, 3) As the reviewer states, this limitation only affects global UV measurements as TOC observations do have a standard methodology for the temperature correction. The term "in global UV irradiance measurements" has been added in line 336.

- (1) Lines 412–413: The influence of this effect seems negligible compared to the other factors considered in the study. Since it is also somewhat off-topic, I suggest removing this sentence.

(2, 3) Following the comments made by all reviewers, lines 412–413 have been removed from the manuscript.

- (1) Line 449: Remove the word "likely". These uncertainties are certainly highly underestimated.

(2, 3) The word “likely” has been removed from the manuscript.

- (1) Line 460: Is the correct term here accuracy or precision?

(2, 3) In the indicated context, accuracy is the correct term. Therefore, the word “precision” has been replaced with “accuracy”.

- (1) Lines 462–463: Although it may be technically correct to state that uncertainty increases with increasing wavelength and decreasing SZA, this is highly misleading. The more relevant quantity is the relative uncertainty, which behaves oppositely. I strongly recommend rephrasing this, and the same applies to lines 695–696.

(2, 3) Noted. To avoid confusion between absolute and relative uncertainty values, the indicated lines have been rephrased by adding the units of the absolute and relative combined standard uncertainty.

- (1) Line 508: Is the 10% "target" agreement based on a specific recommendation or official guideline? If so, please provide a reference.

(2) The 10 % target is usually used in intercomparison campaigns to assess the agreement between instruments (e.g. Bais et al., 2001; Diémoz et al., 2011).

(3) Following the reviewer’s comment, references have been added in line 508 to provide context for the 10 % target used.

- (1) Line 530: Dead time does not appear to be a dominant factor for most of the instruments listed, perhaps only for #202.

(2, 3) As the reviewer states, it is only important for Brewer #202. Therefore, the term “dead time correction” has been removed from line 530.