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 spectroradiometers". The authors thank the Reviewer for the careful and constructive examination of the manuscript and reply to all their comments below.

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

(1) GENERAL COMMENTS

(1) The study by González et al. builds upon previous work by the same authors (https://doi.org/10.1029/2023JD039500), extending the methodology applied to Brewer #150 to a broader set of Brewer spectrophotometers participating in an RBCC-E campaign. The authors discuss various factors influencing the uncertainty in spectral UV measurements and estimate the overall uncertainty using a Monte Carlo approach. A notable limitation, however, is that approximately half of the instruments were not fully characterized, for instance lacking angular response measurements. An additional contribution beyond the 2023 study is the inclusion of stray light effects, addressed here using a method originally developed for direct-sun observations and never demonstrated to work on global UV irradiance.

(2, 3) A statement has been added to the text to acknowledge the incomplete characterisation of several instruments, and, as a result, their limited uncertainty evaluation. Moreover, this limitation has become apparent when comparing these instruments with the QASUME unit (the comparison and its uncertainty has been added in Section 4, Results). As for the stray light, the methodology has been modified to incorporate the standard correction implemented in EuBrewNet (five-wavelength method). This method has also been used in previous uncertainty evaluation studies for both UV and AOD measurements (Arola and Koskela, 2004; Garane et al., 2006).

(1) The general topic is of high relevance to both the Brewer user community and the broader scientific community, particularly in the context of long-term UV trend detection related to ozone variability and climate change. Nevertheless, the manuscript contains several inaccuracies and errors concerning the description of the Brewer instrument. Furthermore, the methodology is presented in a confusing manner, frequently confounding systematic effects with the uncertainties introduced by their corrections. The improper distinction between systematic and random effects appears to result in absurd outcomes, for example, an estimated uncertainty in the UV Index of only 0.28–0.53%, which is significantly lower than the stated calibration uncertainty of the irradiance standard lamps used for Brewer calibration.

(2, 3) The inaccuracies and errors found in the description of the Brewer spectrophotometer have been corrected (Section 2 of the manuscript). The methodology section has been corrected as well, to specifically include the difference between errors and the uncertainties produced by their correction. As for the results obtained, the calculation of the UV index was revised, finding that it was wrongly implemented. Therefore, the UV index has been recalculated, now reporting uncertainties of 2.7–6.2 %. Furthermore, to ensure the credibility of the uncertainties estimated in this work, they have been compared to the ones found in previous studies. In this way, the combined standard uncertainty, UV index, and the uncertainties produced by the sources of error characterised in this study are similar to the ones reported in other Brewer spectrophotometers and UV spectroradiometers (Section 6 of the manuscript).

(1) I strongly recommend against publication of the manuscript in its current form, as it risks disseminating incorrect and potentially misleading information to the user community.

(2) Following the reviewer's comment, the manuscript has been corrected and improved. Moreover, the methodology has been revised and the uncertainty estimations recalculated, which has led to irradiance, UV index, and erythemal uncertainties similar to those found in previous studies.

(1) SPECIFIC COMMENTS

(1) 1. Scope of the paper

(1) The scope and applicability of the results remain unclear. For instance, it appears that the calculated uncertainties pertain to measurements performed during the RBCC-E campaign. However, a long-term drift in Brewer responsivity of 3 % is then mentioned: clarification is needed on whether this drift refers to a time span that includes or exceeds the duration of the campaign. Additionally, it is not clear whether the stray light correction method described in the manuscript was actually implemented during the campaign, or if the cosine correction was actually applied to the data described in the campaign report.

(2) The measurements (and their corrections) considered in this study were performed during the 18th RBCC-E campaign. This includes stray light for single Brewers as well as cosine and temperature correction for those double Brewers that had such sources characterised. The cosine correction applied improved considerably the comparison to the QASUME, as stated in the campaign report (Hülsen, 2023). However, there is one uncertainty source considered that was characterised using the calibration data set of Brewer spectrophotometers: radiometric stability. Several studies recommend characterising the instability of an instrument by studying the difference between consecutive calibrations (either by deriving the standard deviation or the rms uncertainty) (Webb et al., 1998; Bernhard and Seckmeyer, 1999). These methods require the instrument to be calibrated frequently so as to derive appropriate statistics. During the 18th RBCC-E campaign, Brewers were calibrated once using one or two 1000 W lamps. Therefore, no reliable standard deviation can be obtained from the calibrations taken during the campaign. Since most of the Brewers used in this study are usually calibrated once a year (or even once every two years), no short-term monitoring uncertainty could be derived either. As a result, all available calibration records were considered. Furthermore, the radiometric uncertainty depends on the instrument as well as on its modifications and maintenance. This further complicated the determination of the radiometric uncertainty for each Brewer as most of them have been operating for several years and have undergone many modifications throughout this time. In the end, only two Brewers had enough calibration records to derive this uncertainty: Brewer #185 and #150. For the remaining Brewers, a 3 % uncertainty was assumed, in agreement with the findings of Garane et al. (2006) and Lakkala et al. (2008).

(3) To clarify this issue, the time when measurements were performed as well as their corrections and uncertainty characterisation has been clarified in the methodology section. As a result, in Line 145 (beginning of the methodology section) the following information has been added: "The UV measurements used for the uncertainty evaluation were performed during the 18th RBCC-E intercomparison campaign (described in detail in Section 2.2.)". Moreover, an explanation regarding the corrections and their uncertainties have been added in Section 3.1 (characterisation of the uncertainty sources): "All these sources and their corresponding corrections have been applied to the Brewer UV measurements during the 18th RBCC-E campaign, whenever possible.

As will be described in the following, some of the participating Brewers were not fully characterised, lacking information regarding their temperature and cosine correction. The uncertainty sources included in the uncertainty evaluation of each Brewer are summarised in Table 2.

Table 2. Summary of the uncertainty sources considered for each Brewer under study. Red squares (–) represent the uncertainty sources not included in the evaluation, while green squares (×) indicate those uncertainty sources considered.

Uncertainty sources considered	Brewer ID									
	#117	#150	#151	#158	#172	#185	#186	#202	#228	#256
Noise	×	×	×	×	×	×	×	×	×	×
Dark signal	×	×	×	×	×	×	×	×	×	×
Stray light	×	–	×	–	–	–	–	–	–	–
Dead time	×	×	×	×	×	×	×	×	×	×
Distance adjustment	×	×	×	×	×	×	×	×	×	×
Uncertainty of the reference lamp	×	×	×	×	×	×	×	×	×	×
Radiometric stability	×	×	×	×	×	×	×	×	×	×
Wavelength shift	×	×	×	×	×	×	×	×	×	×
Temperature correction	–	×	–	–	–	–	–	–	–	–
Cosine correction	–	×	–	×	–	×	×	–	–	×

Furthermore, the data used to determine the stability uncertainty has been provided in line 244 (Section 3.1.2): "On the other hand, the uncertainty assumed (3 %) is also similar to the average uncertainty found for Brewers #150 and #185, of 2.9 % and 2.4 %, respectively. For Brewer #150, the radiometric uncertainty was derived using the yearly calibration files from 2005 to 2023, while for Brewer #185 the uncertainty was calculated using the monthly calibration files recorded from 2021 to 2024. As mentioned earlier, no data from prior years could be used as the entrance optics of Brewers #150 and #185 were replaced in 2005 and 2021, respectively".

(1) 2. Inaccuracies and errors in the description of the Brewer spectrophotometer

- (1) Line 97: Global spectral UV radiation reaches the foreoptics after two prism reflections (UV-B prism and zenith prism), not one

  (2, 3) The phrase has been corrected to: "global UV irradiance enters through the entrance optics, consisting of a Teflon diffuser covered by a quartz dome, and is redirected into the fore-optics using two prisms (UV-B and zenith prisms)".

- (1) Lines 97–98: Filter Wheel #3 is typically set to the open position

  (2) Filter Wheel #3 contains different filters for each measuring mode: (1) a UG-11/NiSO4 filter for ozone mode, (2) a BG-12 filter for NO2 mode of operation, and (3) a UG-11 filter for UV measurements (Kipp & Zonen, 2007). Maybe the reviewer is referring to Filter Wheel #1, which is set to the open position for UV measurements for both types (MkIII and MkIV) of Brewer spectrophotometers (Kipp & Zonen, 2007, 2018).

  (3) The following description of the three filter wheels has been added to the manuscript: "The first filter wheel has an open hole (open position) for UV measurements, a ground-quartz disk (pos. 1) for direct-Sun measurements and an opaque disk (pos. 2) for dark signal tests (Kipp & Zonen, 2007, 2018). The second filter wheel contains five neutral

density filters to adjust the intensity level of the incoming light. After passing the filter wheels, the light is focused onto the spectrometer”. Then, after describing the spectrometer and the slit mask (see the response to the specific comments), Filter Wheel #3 has been described as: “In MkIV Brewers, the emerging light passes through a third filter wheel, which has several filters to block undesired radiation: (1) in the ozone mode, a UG-11/NiSO4 filter combination is used, (2) in the UV mode, the filter switches to a UG-11 filter, and (3) in the NO2 mode, a BG-12 filter is used to block UV radiation (Kipp & Zonen, 2007)”.

- (1) Line 98: Filter wheels are mechanical components used to position optical elements, but are not optical elements themselves

(2, 3) The discussion regarding the filter wheels has been separated from the one regarding the optical elements. As a result, line 98 has been rewritten as: “The incoming radiation is then focused and collimated by the Iris diaphragm. Then, the intensity of the beam is adjusted before entering the spectrometer, using two filter wheels”.

- (1) Line 105: MkIV Brewers use the third diffraction order for UV measurements. The diffraction grating has 1200 lines per ***mm***, not 1800 lines per ***nm*** as stated

(2, 3) The diffraction order of MkIV Brewers has been corrected, as well as the units corresponding to the line density of the diffraction grating.

- (1) Line 108: The correct specification is 3600 lines per ***mm***, not ***nm***

(2, 3) The term “nm” has been replaced with “mm”.

- (1) Line 108: According to the diffraction equation, identical diffraction angles for a given wavelength occur with 1200 lines/mm in third order and 3600 lines/mm in first order

(2, 3) The phrase “smaller diffracted angles than for double monochromator Brewers” has been removed from the manuscript.

- (1) Line 116: The Brewer slit function is better described as trapezoidal, not triangular (e.g., https://acp.copernicus.org/articles/14/1635/2014/)

(2, 3) The term “triangular” has been replaced with “trapezoidal”.

- (1) Line 208: The statement “using the DT tests, this constant is frequently checked and updated when necessary” is misleading, especially after the claim that the dead time value is stored in the B-files. This could wrongly imply real-time updates. Furthermore, DT test results are highly sensitive to the intensity of the standard lamp (SL), making their use as an uncertainty estimate questionable. In practice, the dead time is more reliably verified through ozone direct-sun (DS) comparisons during calibration audits

(2) As the referee states, DT is not real-time updated, it is usually updated during calibration audits. As for its uncertainty estimation, both methodologies, the one using the standard lamp (SL) and the one using direct-sun (DS) measurements, have their limitations. The former may occasionally result in noisy results when the intensity of the SL is weak. On the other hand, the latter (DS measurements) can also lead to uncertain results when the Sun is covered (partially or fully) by clouds. In this study, the SL method was used and the results reported are similar to those obtained using solar DS

measurements. For example, the DT uncertainties estimated in this study and their resulting contribution are similar to the ones obtained by Fountoulakis et al. (2016b) (https://doi.org/10.5194/amt-9-1799-2016)

(3) To clarify this issue, the phrase "this constant is frequently checked and updated when necessary" has been modified to "this constant is frequently checked and updated during calibration audits". Furthermore, the following sentence has been added to Section 3.1.1 (error sources affecting Brewer signal): "The dead time uncertainties found using the previous methodology are similar to those reported by Fountoulakis et al. (2016b). They determined standard deviations of 1–2 ns for the Brewer dead time using direct-Sun measurements". Moreover, following the comments made by Reviewers #1 and #3, the following information has been added to former Section 4.2.4. (irradiance uncertainty produced by the dead time correction): "Finally, the irradiance uncertainties previously estimated can be compared to the one reported by Fountoulakis et al. (2016b). Their study shows that if the DT ranges from 15 to 45 s and has an error of 2 ns, it leads to irradiance uncertainties of 0.12–0.13, 0.25–0.28, and 0.69–1.13 % for signals of 1, 2, and 5 million counts s^{-1}, respectively. These values are similar to the ones found for all Brewers, except Brewer #202, which has an uncertainty larger than 2 ns. For these Brewers, the irradiance uncertainty is less than 0.15, 0.35, and 0.9 % for signals of 1, 2, and 5 million counts s^{-1}, respectively"

- (1) Line 263: Many modern Brewers are now equipped with heaters, thus minimizing internal temperature fluctuations

  (2) Modern Brewers have heaters that are switched on when the internal temperature of the instrument drops below a specified value. The minimum temperature can be set at 10 °C or 20 °C (Kipp & Zonen, 2018). Therefore, these heaters are used to avoid operating at very low temperatures, but they do not control the internal temperature of the instrument. During the 18th RBCC-E campaign, hosted in the southwest of Spain in summer, the internal temperature of the Brewers fluctuated greatly, between 20 and 42 °C.

  (3) The previous information has been added to the text as follows: "Brewer spectrophotometers are operated within a weather-proof housing and have electrical heaters to prevent operation at low temperatures. If the internal temperature of the instrument falls below 10 °C or 20 °C (Kipp & Zonen. 2018), these heaters are automatically switched on. Nevertheless, the Brewer internal temperature is not stabilised and can fluctuate throughout the day".

- (1) Lines 465–466: A more accurate phrasing would be: "The instrument is calibrated using the standard lamps with the input optics positioned at zenith."

  (2) Lines 465–466 correspond to the irradiance uncertainty caused by the errors committed during the distance adjustment. They describe that the uncertainty sources affecting the responsivity (distance, uncertainty of reference lamp, and radiometric stability) have no angular dependency. Maybe the reviewer is suggesting rephrasing another part of the manuscript.

  (3) To take into account the calibration procedure mentioned by the reviewer, the suggested phrase has been added in Section 2 (description of the instrument) as "As for their calibration, the instrument is calibrated using reference lamps (usually 1000 W

lamps) with the input optics positioned at zenith". The term "standard" has been replaced with "reference" to differentiate between the lamps used for the radiometric calibration and the standard lamp that is inside the Brewer spectrophotometer.

(1) 3. Treatment of stray light

(1) The application of the algorithm proposed by Savastiouk et al. (2023) to spectral UV irradiance measurements raises several concerns. According to their paper, this method was specifically developed for direct-sun observations conducted at a fixed grating position and was not validated for use at other wavelengths or for measurements requiring grating movement, such as those involved in spectral UV irradiance scans. Additionally, spectral UV irradiance measurements are not performed simultaneously across wavelengths, further complicating the applicability of the method to this context.

The validity of applying this correction approach should be demonstrated, ideally through comparisons of corrected UV spectra from single-monochromator instruments with measurements from reference instruments with negligible stray light effects. Alternatively, the uncertainty introduced by the application of this stray light "model" should be explicitly quantified, in addition to the two uncertainty sources discussed in lines 181–182.

The manuscript states that "deriving the uncertainty of this [the 5-wavelength] method for the Brewers under study is difficult, as it would use the information from only five wavelengths." However, it remains unclear what correction method, if any, was actually employed during the RBCC-E campaign. Moreover, the statement regarding the difficulty of the 5-wavelength approach is vague. The authors should clarify what specific challenges prevent its application and provide justification for the selected correction method.

(2) During the RBCC-E campaign, the stray light was corrected using the five-wavelength method, according to EuBrewNet's processing algorithm (https://eubrewnet.aemet.es/dokuwiki/doku.php?id=codes:uvaccess, last access: 29 May 2025). Then, the corrected spectra were compared against the reference unit QASUME (Hülsen, 2023). At first, this approach was discarded as it would also consider, besides the stray light effects, the temperature and the cosine error of the instrument (single Brewers are not corrected for these two error sources). Nevertheless, the effect of these two sources is expected to be small below 292 nm. As a result, the uncertainty determined in this way is not a huge overestimation of the uncertainty produced by stray light correction. Furthermore, since the stray light was estimated during the RBCC-E campaign using the five-wavelength method, the uncertainty should be estimated using the suggested approach (comparison to the QASUME) instead of the one proposed by Savastiouk et al. (2023).

(3) Following the reviewer's comment, the methodology implemented by Savastiouk et al. (2023) has been replaced with the one used in the RBCC-E campaign. As a result, the description in lines 168–184 has been changed to "The uncertainty of this method was estimated by comparing the corrected irradiance to the QASUME from 290 to 292 nm. This estimation also includes the effects of temperature and cosine errors since the single Brewers under study are not corrected for these two sources of error. Nevertheless, since the effect of these two sources is expected to be small below 292 nm, the uncertainty determined might be only a slight overestimation. Furthermore, the standard deviation from the measurements of the five wavelengths (from 290 to 292 nm) was also derived and combined with the uncertainty obtained from the QASUME comparison". Furthermore, the results section has been updated to reflect the new stray light

correction methodology. As a result, all figures in sections 4.1 and 4.2 have been modified. Finally, the abstract and conclusion sections of the manuscript have also been revised and changed when necessary.

(1) 4. Treatment of systematic error sources

(1) 4a. Ambiguity in use of terminology

(1) According to the Guide to the Expression of Uncertainty in Measurement (GUM), all known systematic error sources must be corrected prior to uncertainty estimation, with the residual uncertainty from those corrections included in the total uncertainty budget. This methodological framework is not clearly articulated in the manuscript, particularly in the methodology section, and the terminology used throughout the manuscript often conflates systematic errors with uncertainty contributions.

For example, lines 26–28 state: "For wavelengths below 300 nm, the differences between single- and double-monochromator Brewers increase, due to stray light and dark counts. For example, at 295 nm, the relative uncertainties of single Brewers range between 11–14% while double Brewers have uncertainties of 4–7%." This wording implies that stray light is itself a source of uncertainty, rather than a systematic (albeit variable) error that should be corrected. A similar ambiguity is present in lines 449–450: "the contribution of stray light increases rapidly as wavelength decreases." It is unclear whether this refers to the increasing magnitude of the stray light error or to the uncertainty associated with correcting it. The same confusion is evident in the discussion of cosine correction.

The authors should explicitly distinguish between systematic effects (which must be corrected) and the uncertainties associated with those corrections.

(2, 3) Noted. All sections of the manuscript have been revised to differentiate clearly between the sources of error and the uncertainty caused by their correction. For example, lines 26–28 have been rephrased to "the differences between single- and double-monochromator Brewers increase, due to the uncertainty in stray light correction". On the other hand, lines 449–450 have been corrected to "The sensitivity analysis shows that the irradiance uncertainty produced by stray light correction increases rapidly as wavelength decreases". Furthermore, for greater clarity, the following description of the terms "error" (both systematic and random) and "uncertainty" has been added in the methodology section, at the beginning of section 3.1.: "Error sources are usually separated into random and systematic components. Random errors produce variations in repeated measurements and as such, are usually reduced by increasing the number of observations (BIPM et al., 2008a). On the other hand, systematic errors can be compensated by applying a correction factor to the irradiance measured. Even if all errors are appropriately characterised and corrected, there still remains a doubt, an uncertainty, about the accuracy of the reported result (BIPM et al., 2008b). In the following, the term "error" will denote the imperfections in a measurement result, while the term "uncertainty" will be used to reflect the existing doubt regarding the value of the measured spectral UV irradiance. In this way, it is important to differentiate between the source of error (for example cosine error) and the uncertainty associated with its correction".

(1) 4b. Effectiveness of corrections

(1) To justify the inclusion of systematic error corrections, the authors must demonstrate that these corrections lead to improved measurement accuracy. This could be done by presenting plots showing the relative (%) differences between corrected spectra and a reference standard (e.g.,

QASUME). Such comparisons would help assess the effectiveness of the applied stray light and cosine corrections. The residual discrepancies should then be discussed in the context of the total uncertainty budget.

(2) The corrections considered in this study (cosine error, temperature, stray light, etc.) have been proven to be effective by numerous studies (e.g. Fountoulakis et al., 2016b; Garane et al., 2006; Kerr, 2010; Lakkala et al., 2008, 2018). Moreover, the campaign report also shows that the cosine correction implemented improved the quality of the measurements (Hülsen, 2023). Nevertheless, following the suggestions made by all reviewers, a section has been added in the results of the manuscript to study the ratio of the instruments to the QASUME, the reference unit in Europe.

(3) The following information has been added in the results section:

"The corrections applied to the measured irradiance (described in section 3.2) are recommended by numerous studies to improve the quality of the measurements (e.g. Fountoulakis et al., 2016b; Garane et al., 2006; Kerr, 2010; Lakkala et al., 2008, 2018). This was also verified during the 18th RBCC-E campaign, as the results show that including the cosine correction improves considerably the comparison to the QASUME (Hülsen, 2023). Although the campaign report shows the ratio of each participating Brewer to the QASUME (see Hülsen (2023)), it is interesting to represent the ratio of all studied Brewers together. In this way, Fig. 4 displays the global irradiance ratio to the QASUME obtained from dividing the irradiances shown in Fig. 1 to the irradiance recorded by the QASUME unit.

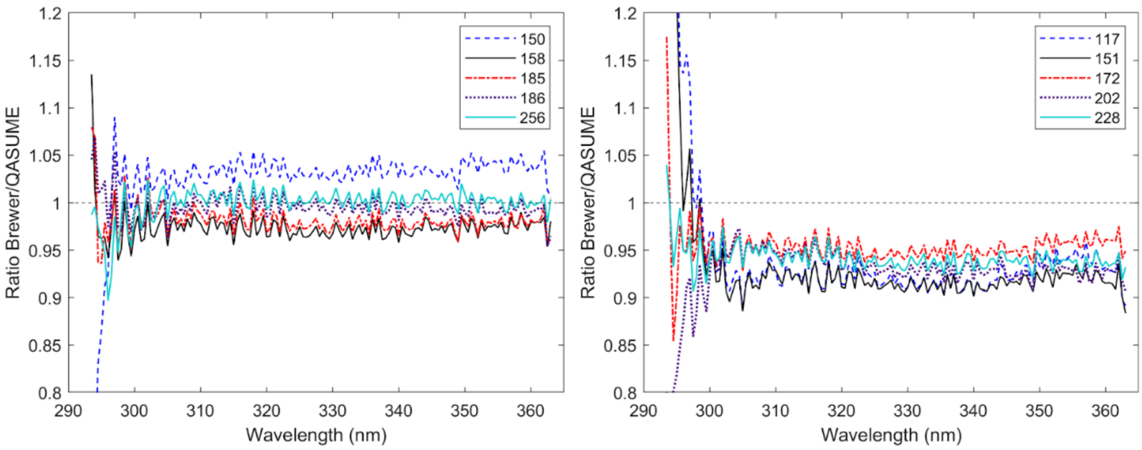

Figure 4. Global irradiance ratio to the QASUME recorded on 13 September at 14:00 UTC. (a) First group (double Brewers with cosine correction). (b) Second group (two single and three double Brewers with no cosine correction implemented).

Figure 4 shows the effectiveness of the cosine correction, since Brewers with such correction implemented (Fig. 4a) report irradiances more similar to the one measured by the QASUME. Nevertheless, the agreement between all Brewer spectrophotometers and the QASUME is within 10 % for wavelengths above 310 nm.

Furthermore, the irradiance uncertainty found for each Brewer in the previous section can be used to derive the uncertainty of their ratio to the QASUME. Table 3 summarises the combined standard uncertainty of the average Brewer/QASUME ratio measured on 13 September at three different wavelengths. These uncertainties were computed by combining the irradiance uncertainty of each Brewer and the one from the QASUME, provided by Hülsen et al. (2016).

Table 3. Number of simultaneous scans, mean ratio to the QASUME and its combined standard uncertainty (both absolute and relative) determined between 310 and 360 nm on 13 September.

Brewer ID	N	Ratio to the QASUME (310–360 nm)		
		Mean value	Combined standard uncertainty	Relative standard uncertainty (%)
#117	19	0.927	0.034	3.7
#150	20	1.035	0.035	3.4
#151	24	0.914	0.033	3.6
#158	17	0.972	0.036	3.7
#172	19	0.947	0.033	3.5
#185	18	0.978	0.030	3.1
#186	15	1.003	0.043	4.3
#202	19	0.928	0.033	3.6
#228	19	0.937	0.033	3.5
#256	19	1.003	0.037	3.7

Table 3 shows that only those Brewer spectrophotometers with a cosine correction implemented (#150, #158, #185, #186, and #256) include the ideal value of the ratio (unity) within their uncertainty interval. The remaining Brewers underestimate the UV irradiance and deviate from unity. This is likely caused by the cosine and temperature errors of the instruments, which couldn't be corrected (there was no available information regarding their characterisation). Therefore, to improve the performance of these uncorrected Brewers these two sources must be characterised and corrected".

(1) 4c. Missing information for some Brewers

(1) Only five Brewer instruments were characterized for their angular response, yet cosine correction is an essential component of systematic error treatment. Given this limitation, the authors should consider restricting their analysis to only those instruments for which a full angular characterization was performed.

(2) It is well-known that cosine correction is an important source of uncertainty of the Brewer UV measurements. As a result, several studies have proposed different methodologies to characterise the angular response and then correct the cosine error (Antón et al., 2008; Bais et al., 2005; Gröbner et al., 1996; Lakkala et al., 2018). Even if all these methods exist, the RBCC-E intercomparison campaign held at the El Arenosillo station in 2023 showed that the irradiances of most Brewers were not corrected for cosine error. Since the characterisation of these instruments is incomplete, so is their uncertainty analysis. Nevertheless, the aim of this study is to evaluate the uncertainty of the spectral irradiance currently reported by most of the Brewers. That is why in the conclusions section we emphasise the difficulties found when trying to evaluate the uncertainty of the Brewers. If the analysis is restricted to the Brewers that are completely characterised, it wouldn't be representative of the current state of the Brewer network. Nevertheless, this limitation should be explicitly acknowledged in the manuscript.

(3) Following the reviewer's comment, the following information has been added at the beginning of the results section (line 363) "The uncertainty evaluation of the Brewer spectrophotometers in this second group is limited as it is missing one of the key uncertainty sources in solar radiometry, cosine correction. As a result, the uncertainties determined are likely an underestimation. Nevertheless, these estimations represent the uncertainty of the spectral irradiance reported by most of the participating Brewer spectrophotometers".

(1) 4d. Uncertainty in cosine correction

(1) The uncertainty associated with the direct-to-global ratio (DIR/GLO) has not been addressed in the manuscript. This is a significant omission, as this uncertainty can be non-negligible, particularly under overcast or mixed sky conditions. By excluding it, the analysis is effectively constrained to clear-sky scenarios. This limitation should be explicitly acknowledged and clearly stated in the discussion.

(2) Indeed, the cosine correction implemented in this study is valid under cloud-free conditions. Consequently, the results of the uncertainty analysis have been limited to clear-sky scenarios.

(3) The discussion section has been modified to: "The uncertainty evaluation was performed for all the UV scans measured during the campaign under cloud-free conditions". Furthermore, following the comments made by Reviewers #1 and #3, a remark has also been added regarding the appropriate methodology for cloudy conditions: "Under cloudy conditions, the methodology for calculating the cosine correction and noise must be adapted accordingly. As the cosine correction depends on the cloudiness, the cloud cover must be considered when modelling the direct-to-global ratio".

(1) 4e. Uncertainty in wavelength alignment

(1) Section 4.2.8 addresses wavelength alignment uncertainty, but the proposed treatment is incomplete. The wavelength shifts should first be minimized through the application of an improved dispersion equation, after which any residual shifts can be analyzed to assess temporal variability. Ignoring this step may overestimate the uncertainty or fail to correct for avoidable errors.

(2) Ideally, a wavelength recalibration should have been performed during the RBCC-E campaign. Nevertheless, the irradiances measured by these instruments (#151 and #158) are affected by the wavelength shifts reported in section 4.2.8. However, this limitation should be clearly acknowledged and a remark should be made on how to avoid these large errors.

(3) Following the reviewer's comment, the following information has been added in section 4.2.8: "These large wavelength shifts indicate that the dispersion function of these instruments might be outdated. Therefore, special attention should be paid to the wavelength scale of the instrument by performing frequent and accurate wavelength calibrations". Furthermore, in the conclusions section, this limitation has been stated as "Based on the findings of this sensitivity analysis, to reduce the overall uncertainty of a Brewer spectrophotometer, it is recommended to [...] (e) monitor wavelength shifts and reduce them below 0.05 nm through frequent wavelength calibrations and accurate determinations of the instrument wavelength scale".

(1) 4f. Separation of systematic and random error sources

(1) There appears to be a fundamental issue in how error sources are classified and treated. It seems that all sources of error were handled as random, without distinguishing between random and systematic effects. This approach leads to implausible outcomes, such as the claim that the UV Index can be determined with an uncertainty (0.28–0.53%) lower than that of the irradiance calibration lamps themselves (line 538). The authors should clearly explain how systematic and random error sources were identified and subsequently treated in the uncertainty analysis.

(2) The uncertainty analysis has been carried out following the recommendations of the Guide to the expression of Uncertainty in Measurements (GUM). This Guide recommends calculating the

uncertainty "*based on the concept that there is no inherent difference between an uncertainty component arising from a random effect and one arising from a correction for a systematic effect*" (BIPM et al., 2008b). Therefore, this methodology stands in contrast to older methods that recommended separating the sources into "systematic" and "random" and combining the uncertainties associated with each in their own way (BIPM et al., 2008a). This approach results in relative combined standard uncertainties that are similar to the ones found in previous studies (Bernhard and Seckmeyer, 1999; Garane et al., 2006; Hülsen et al., 2016; Fountoulakis et al., 2020). Therefore, the methodology implemented provides coherent uncertainty estimations. Nevertheless, the Monte Carlo simulation was wrongly adapted for the calculation of the UV index uncertainty. The propagation of the PDFs of the uncertainty sources was incorrect and, as a result, the determined uncertainty was way too small. Following the methodology of Cordero et al. (2007), the Monte Carlo simulation implemented for the uncertainty evaluation of the UV index has been revised and corrected.

(3) The information regarding systematic and random errors have been added in the methodology section as "Error sources are usually separated into random and systematic components. Random errors produce variations in repeated measurements and as such, are usually reduced by increasing the number of observations (BIPM et al., 2008a). On the other hand, systematic errors can be compensated by applying a correction factor to the irradiance measured". Then, in section 3.3 (Monte Carlo method) the combination of their uncertainty has been described as follows: "Following the GUM guidelines, the uncertainty arising from random and systematic errors have been treated identically (BIPM et al., 2008b)". As for the UV index, its uncertainty has been recalculated and the values reported in section 5 have been modified to "When integrating erythemal spectral irradiance to compute the UV Index (UVI), the resulting uncertainty ranges from 2.7 % to 6.2 %". Finally, in the conclusions section, a brief comparison of these values to the ones found in other studies has been added. In this way, the following information has been included in line 625 "Therefore, the relative combined standard uncertainties determined in this study are comparable to those of other UV spectroradiometers. This also applies to the uncertainties of erythemal irradiance and UV index, as the values estimated are also similar to the ones found for other instruments (Bernhard and Seckmeyer, 1999; Cordero et al., 2007)".

(1) 5. Calibration and measurements

(1) In standard practice, the uncertainty budget for UV irradiance measurements is assessed in two distinct phases: one for the calibration process and one for actual solar measurements (e.g., Bernhard and Seckmeyer, 1999). This distinction is important because calibration is itself a measurement procedure and shares several uncertainty sources with field measurements. Typically, the uncertainty associated with the calibration is propagated and added to the overall uncertainty of the spectral UV irradiance. Given that the authors employed a Monte Carlo method, it would be expected that the analysis reflects this two-phase approach, explicitly separating and then combining the calibration and measurement uncertainties. This methodological structure appears to be missing from the current work.

(2) There is no need to separate the uncertainty sources into two phases as the Monte Carlo method allows to vary all uncertainty sources at once. At each iteration of the Monte Carlo simulation, the signals measured outdoors and under the reference lamp are varied according to the PDFs of their uncertainty sources (noise, dead time, stray light, and dark signal). The irradiance of the reference lamp is also varied according to its uncertainty (distance adjustment and calibration certificate) and the responsivity is recalculated using the new values. Then, using the new values

of the outdoor signal and the responsivity, the corresponding UV irradiance is obtained. Finally, this irradiance is also varied according to the uncertainties produced by the wavelength misalignment, cosine, and temperature correction. A flow chart of this process can be found in González et al. (2024b). Although it is not necessary to separate the uncertainty analysis into two phases, it can be interesting to calculate the uncertainty of the calibration process by only considering the uncertainty sources described in sections 3.1.1 and 3.1.2 for the signal measured during the calibration and the responsivity, respectively.

(3) To make it clear that the calibration procedure also includes the uncertainty sources affecting field measurements, the following information has been added in section 3.1.2 "Then, the signal under the lamp is recorded several times and corrected for dark counts, dead time, and stray light (see Section 3.1.1.). The responsivity of the instrument is derived by dividing the corrected signal by the irradiance of the reference lamp. However, this responsivity is also affected by other sources of uncertainty produced during the radiometric calibration such as the distance adjustment between the lamp and the diffuser, the radiometric stability, and the uncertainty of the spectral irradiance emitted by the reference lamp". Furthermore, the irradiance uncertainty produced solely by the calibration procedure has been added in the sensitivity analysis (former section 4.2) as "Regarding the calibration of the instrument (uncertainty sources affecting the responsivity and the signal measured under the reference lamp), it leads to irradiance uncertainties that range from 2.3 % (Brewer #185) to 3.8 % (Brewer #150)".

(1) 6. Bibliographic references

(1) The bibliography omits several relevant studies related to uncertainty analysis in Brewer spectrophotometer measurements. Notably, valuable insights can be found not only in works addressing UV irradiance, but also in studies focused on trace gas retrieval and aerosol optical depth (AOD) measurements using the Brewer in direct-sun mode. These references often include rigorous uncertainty analyses that could enhance the methodology of this study. The authors should broaden the literature review to incorporate these contributions.

(2) As previously discussed, the measuring procedure is different for global UV irradiance (the diffraction gratings rotate while the slit mask is fixed) and direct-Sun (the diffraction gratings remain fixed while the slit mask rotates) observations. As a result, most of the sources of error affecting these measurements are different. For example, López-Solano et al. (2018) estimate the uncertainty of Brewer AOD by considering the uncertainties arising from ozone optical depth, pressure, and calibration (carried out by transfer or by a Langley plot). None of these sources are relevant in the uncertainty evaluation of UV irradiance (Bernhard and Seckmeyer, 1999; Webb et al., 1998). Nevertheless, there are some uncertainty sources in common, such as stray light, dead time (nonlinearity), or dark signal. Unfortunately, these sources are not as important for direct-Sun measurements as they are for UV observations. As a result, they are sometimes overlooked in the uncertainty evaluation (e.g. Diémoz et al., 2014; López-Solano et al., 2018; Nuñez et al., 2022). Moreover, the number of rigorous uncertainty analyses is very limited for Brewer spectrophotometers. As a result, the literature review could not be greatly broadened. The contributions of these studies have been incorporated in the methodology section whenever possible.

(3) The contribution of other uncertainty evaluation studies has been added in the methodology section as follows:

- Line 167 has been modified to "It is usual to estimate stray light as the average signal recorded below 292 nm (e.g. Arola and Koskela, 2004; Lakkala et al., 2008; Mäkelä et al., 2016) and the correction is carried out by subtracting this average value from the signal measured at all wavelengths".
- "Moreover, the uncertainties estimated for dead time also agree with the ones applied in other uncertainty evaluation studies for Brewer spectrophotometers (Diémoz et al., 2014)" has been added at line 211.

(1) 7. Section 5

(1) Section 5 could be significantly shortened or removed entirely. Much of the content is either self-evident or repetitive of points that belong more appropriately in the Introduction.

(2, 3) Section 5 was not in the original version of the paper, but it was specifically demanded by the editor to highlight the positive impacts of the study. Thus, following the reviewer's comment, Section 5 has been summarised and part of its information has been moved to the Conclusion section so as to shorten the section, as follows:

- Moved to the Conclusions' section: "For the ten Brewer spectrophotometers analysed in this study, the average combined standard uncertainty in erythemal spectral irradiance ranges between 2.7 % and 3.9 %, with maximum values varying from 17 % for a single Brewer to 3.4 % for a double Brewer for wavelengths above 310 nm. This variability indicates the need of characterising each Brewer spectrophotometer individually rather than relying on generic values, which may not fully exploit the precision these instruments can achieve (Gröbner et al., 2006). When integrating erythemal spectral irradiance to compute the UV Index (UVI), the resulting uncertainty ranges from 2.7 % to 6.2 %. The UVI, along with cumulative erythemal irradiance doses, represents a fundamental metric for informing the public about the potential adverse effects of UV radiation (Lucas et al., 2019)."
- Summarised section 5: "This study provides an accurate quantification of measurement uncertainties in Brewer spectrophotometer UV data, identifying the main sources of uncertainty and their relative contributions to guide instrumental optimisations. These aspects are of great interest for different studies and fields of work.

  One of the key applications of accurately determining the uncertainties in 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). The proposed methodology also allows sensitivity analysis to help identify paths for improving instrumentation, measurement procedures, and calibration protocols, which are essential for ensuring the traceability of UV spectroradiometer measurements to international standards (Gröbner et al., 2006). Reliable measurements in the 300–400 nm wavelength range with a relative uncertainty below 4 % are crucial for radiometric networks and studies comparing data from different stations. Ensuring this quality level requires periodic and regular calibrations using lamps traceable to international standards. For example, the QASUME (Quality Assurance of Solar Ultraviolet Spectral Irradiance Measurements) project has established a European reference standard for UV solar radiation measurements, achieving a global UV irradiance uncertainty of approximately ±4 % in the 300–400 nm range (Gröbner and Sperfeld, 2005) and a direct solar irradiance uncertainty of about 0.7 % (Gröbner et al., 2023). More advanced developments, such as QASUMEII, have further improved accuracy, with a combined uncertainty for global UV measurements of 1.01 % between 310 and 400 nm and 3.67 % at 300 nm (Hülsen et al., 2016).

Furthermore, the uncertainty framework significantly strengthens the validation of satellite-based UV products from instruments such as OMI, TROPOMI, and TEMPO (Klotz et al., 2024; Tanskanen et al., 2007), where ground-based measurements with an uncertainty of less than 5 % are crucial for calibration.

In summary, precise quantification of uncertainty in spectral UV measurements benefits a broad range of scientific, regulatory, and public health applications, reinforcing the need for rigorous uncertainty assessment in Brewer spectrophotometer measurements".

(1) TECHNICAL REMARKS

- (1) The terminology used for the Brewer instrument should be standardized throughout the manuscript. The correct and commonly accepted term is "Brewer spectrophotometer". The inconsistent use of terms such as "spectroradiometer" or "spectrometer" is confusing. If the authors want to emphasize the Brewer's capability to measure global irradiance, the more general term Brewer "instrument" may be appropriate in that context.

  (2, 3) Noted. The terms "spectroradiometer" and "spectrometer" have been replaced with "spectrophotometer" throughout the manuscript. Whenever appropriate, the term "Brewer instrument" has been used to emphasise that Brewers can also measure global UV irradiance.

- (1) Line 25: Please note that only a limited number of steps in the algorithm are non-linear, and these are likely to represent minor contributors to the total uncertainty.

  (2, 3) Following the reviewer's comment, line 25 has been modified to "considers the nonlinearity of certain steps in the UV processing algorithm". Then, the effect of these nonlinear steps in the uncertainty evaluation of Brewer spectrophotometers is discussed later in the introduction section (in the abstract the number of words is limited and complicates a proper discussion).

- (1) Line 30: The statement that stray light depends simply or solely on UV intensity is inaccurate.

  (2) In line 30 the text is referring to the irradiance uncertainty produced by the stray light correction, which increases as the wavelength decreases (see Fig. 5). It was never the intention to imply that stray light only depends on UV intensity. As indicated in the methodology, stray light is produced by the scatter inside the instrument and the instrument contamination with dust.

  (3) To avoid confusion, the term "correction of" has been added to indicate that it is not the stray light, but its correction which leads to an irradiance uncertainty that increases as the intensity of the UV irradiance decreases.

- (1) Line 57: The phrase "is trying" is outdated as the COST Action Eubrewnet has concluded. Please revise to reflect the current status.

  (2) EuBrewNet is still working on harmonising the procedures for Brewer QA/QC (both direct-Sun and global UV measurements). The Cost Action 1207 has finished, but its webpage (also named EuBrewNet) and UV processing algorithms are still operational, thanks to AEMET (the State Meteorological Agency from Spain). Any registered user can access, download, and process UV and ozone products from Brewer spectrophotometers that are part of the EuBrewNet community at https://eubrewnet.aemet.es/eubrewnet.

  (3) To clarify this issue, the indicated phrase has been rewritten as: "In this context, EuBrewNet (European Brewer Network), originally developed through COST Action 1207 and currently operational thanks to AEMET (Spanish State Meteorological Agency), is working on harmonising and developing coherent practices for Brewer QA/QC".

- (1) Line 60: Appropriate bibliographic references on the "well-established QA for UV measurements" must be included.

  (2, 3) Following the comments made by Reviewer #2, the phrase "well-established QA for UV measurements" has been replaced with a description of the QA performed by during the RBCC-E intercomparison campaigns and a brief discussion on how this procedure reflects the guidelines of Webb et al. (2003). Furthermore, to take into account the suggestions of Reviewer #3, bibliographic references have been added to back these claims. Therefore, line 60 has been modified to: "These intercomparison campaigns meet the main requirements laid out by Webb et al. (2003), i.e. transparency and objective comparison algorithms (see the campaign reports at the PMOD/WRC website, https://www.pmodwrc.ch/en/world-radiation-center-2/wcc-uv/qasume-site-audits/, the report of the 18th intercomparison campaign, Hülsen, 2023, and an overview of the EuBrewNet's algorithms, López-Solano, 2024)".

- (1) Line 61: Please clarify whether the intended meaning is ozone, UV irradiance, or both.

  (2, 3) QC is a pending task for both ozone and UV irradiance measurements. The previous information has been added to the indicated line: "it remains one of the main challenges for Brewer sites measuring ozone (Fioletov et al., 2008) and UV irradiance".

- (1) Line 96: It should be explicitly stated that a diffuser is used as the global entrance optic for irradiance measurements.

  (2, 3) The following information has been added at line 96: "global UV irradiance enters through the entrance optics, consisting of a Teflon diffuser covered by a quartz dome". Then, on lines 115–121, the different types of entrance optics are described in greater detail.

- (1) Line 99: Please include an explanation that the diffraction grating is rotated during UV spectral scans. Also, provide a description of Filter Wheel #3 (FW#3) for MkIV Brewers.

  (2, 3) Following the reviewer's comment, the explanation of the ozone and UV mode has been added to the manuscript: "At the exit of the spectrometer, there is a cylindrical slit mask. For ozone, dead time, and dark signal observations, the diffraction grating is fixed while the slit mask rotates, selecting in this way the wavelength. On the other hand, for the measuring of UV irradiance, the slit mask remains fixed, and the diffraction grating rotates (using a micrometre) to select the wavelength.”. Furthermore, a description of Filter Wheel #3 has been added as well: “In MkIV Brewers, the emerging light passes through a third filter wheel, which has several filters to block undesired radiation: (1) in the ozone mode, a UG-11/NiSO4 filter combination is used, (2) in the UV mode, the filter switches to a UG-11 filter, and (3) in the NO2 mode, a BG-12 filter is used to block UV radiation (Kipp & Zonen, 2007)”.

- (1) Table 1: The column listing operator names should be omitted. Rather, the characteristics of the diffuser used with each Brewer would be more relevant to the technical discussion.

  (2, 3) The information regarding operators in Table 1 has been replaced with the characteristics of the entrance optics of each Brewer, resulting in the following table:

Brewer	Type (monochromator)	Entrance optics (diffuser)	Institute (Country)
#117	MkIV (single)	Traditional (flat)	State Meteorological Agency – AEMET (Spain)
#150	MkIII (double)	CMS-Schreder (shaped)	National Institute of Aerospace Technology (Spain)
#151	MkIV (single)	Traditional (flat)	State Meteorological Agency – AEMET (Spain)
#158	MkIII (double)	Traditional (flat)	OTT Hydromet (The Netherlands)
#172	MkIII (double)	Traditional (flat)	University of Manchester (UK)
#185	MkIII (double)	CMS-Schreder (flat)	Izaña Atmospheric Research Center, AEMET (Spain)
#186	MkIII (double)	Traditional (flat)	State Meteorological Agency – AEMET (Spain)
#202	MkIII (double)	Traditional (flat)	Danish Meteorological Institute (Denmark)
#228	MkIII (double)	Traditional (flat)	Danish Meteorological Institute (Denmark)
#256	MkIII (double)	CMS-Schreder (flat)	Izaña Atmospheric Research Center, AEMET (Spain)

- (1) Line 110: The cosine error can be mitigated through appropriate correction methods, as discussed in Section 3.1.3.

  (2, 3) Following the reviewer’s comment, this information has been added in line 110 as: “Therefore, a correction is needed to mitigate such deviation, as will be described later in Section 3.1.3”.

- (1) Line 129: Clarify how the angular response characterization was conducted for the two additional Brewers.

  (2) Line 129 contains an error, four Brewers (not three) were calibrated using the Brewer Angular Test. The Brewer remaining (Brewer #158) was calibrated using the operator’s lab cosine setup. This consists of an arm mounted on a solar tracker, which is programmed to turn by steps of 5° in sync with the Brewer CRD routine.

  (3) The mistake in line 129 has been corrected and the following information has been added to the text: “Four of them (#150, #185, #186, and #256) were characterised using the Brewer Angular Tester (BAT), described later in Section 3.1.3. The remaining Brewer (#158) was characterised in the laboratory of its operating site, using a lamp mounted on an arm that turns by steps of 5°”.

- (1) Line 131: Replace “dawn” with “sun rise”.

(2, 3) The term “dawn” has been replaced with “sun rise”.

- (1) Lines 141–142: The names of instrument operators should be moved to the Acknowledgements section.

  (2, 3) The names of the Brewer and QASUME operators have been moved to the Acknowledgements section.

- (1) Line 149: Please provide a proper citation or link to the Eubrewnet guidelines referenced.

  (2, 3) The link to the EuBrewNet guidelines has been added to the manuscript as well as the citation of the overview presented by López-Solano et al. (2024) in the Quadrennial Ozone Symposium meeting.

- (1) Lines 154–155: The rationale for completely ignoring certain uncertainty sources is not adequately justified. It is unclear whether this was actually done and, if so, on what basis.

  (2) Lines 154–155 refer to those uncertainty sources that have been included in the study, but their characterisation is not as thorough as the ones carried out in other studies. For instance, the Brewer noise was determined by studying the signal-to-noise-ratio (SNR) from lamp measurements, as Bernhard and Seckmeyer (1999) or Cordero et al. (2012) did for the uncertainty evaluation of their instruments. However, in the RBCC-E campaign, Brewers were calibrated by performing 4 lamp scans. Therefore, the SNR was derived from a limited number of UV scans. Nevertheless, we believe that, rather than ignoring these uncertainty sources, it is preferable to include them in the study, even if their characterisation is limited.

  (3) Following the comments made by Reviewers #1 and #3 and to clarify this issue, the indicated lines have been rewritten as “It should be noted that some of the uncertainties (such as those related to noise, stray light, or radiometric stability) have not been determined thoroughly, as the data used for their estimation are insufficient to obtain appropriate statistics. Nevertheless, in all these cases, uncertainty values have been given and included in the Monte Carlo simulation”.

- (1) Line 177: The statement that the coefficients are "deemed reliable" is misleading. The two coefficients referenced were derived for ozone and SO_2 retrievals in direct sun mode, not for spectral UV irradiance. Their applicability to spectral UV measurements should be justified.

  (2, 3) Following the reviewer’s general comment on the treatment of stray light, the method proposed by Savastiouk et al. (2023) is no longer included in the uncertainty analysis. As discussed above, the stray light is now corrected using the average counts measured from 290 to 292 nm. Therefore, the indicated lines have been removed from the manuscript and a new discussion regarding stray light has been added (see the response to comment “3. Treatment of stray light”).

- (1) Lines 201–202: All Brewer measurements, not only global UV scans, collect dark count data. Therefore, the authors could have considered a much larger dataset, potentially an order of magnitude more observations per day.

(2) The dark signal measurements from other Brewer observations (such as direct-Sun measurements) have been included in the uncertainty analysis. Therefore, as the referee states, the dataset considered has increased considerably.

(3) Lines 201–202 have been modified to reflect the changes in the methodology: "The number of available measurements depended on the instrument, but, in total, more than 2500 dark signal measurements were recorded by each Brewer during the intercomparison campaign". Furthermore, Section 4.2 (sensitivity analysis) has also been corrected to reflect the new uncertainties. The analysis in lines 441–442 has been changed to "For larger wavelengths, its impact can be disregarded as dark signal correction leads to irradiance uncertainties of less than 0.06 % in double monochromator Brewers".

- (1) Line 215: Please specify which laboratories or types of labs are being referred to.

(2, 3) Following the reviewer's suggestion, the laboratories and a brief description of their calibration standards have been provided in line 215: "These lamps had been previously calibrated in the laboratories of PMOD/WRC and the Finnish Metrology Research Institute, belonging to Aalto University and MIKES. The calibrations performed by PMOD/WRC are traceable to the primary standard of the Physikalisch-Technische Bundesanstalt (PTB) (Gröbner and Sperfeld, 2005). On the other hand, the Metrology Research Institute is the national standard laboratory for optical quantities in Finland and is part of the CIPM Mutual Recognition Arrangement (CIPM MRA), a framework in which metrology institutes prove the international equivalence of their calibrations and certificates".

- (1) Line 219: The text should elaborate on the effect of the current uncertainty.

(2, 3) The following information has been added in Line 219 regarding the uncertainty caused by the current of the reference lamp: "Based on the findings of Webb et al. (1994), the standard practice is to assume that a 1 % change in the current of the reference lamp leads to a 10 % change in the spectral irradiance measured by the instrument (e.g. Bernhard and Seckmeyer, 1999; Webb et al., 1998). According to the previous rule, the expected change in the irradiance of the Brewers under study would be of 0.125 %, as the electrical current was stabilised to within 0.0125 % during their calibration".

- (1) Line 229: Clarify how the reference plane issue for Brewer #150 was resolved.

(2, 3) Following the reviewer's comment, a description of the determination of the reference plane for Brewer #150 has been added at line 229: "This was carried out by placing an ultrastabilised lamp at several distances and measuring its emitted spectrum. The data showed that the diffuser's reference plane is placed (0.234   0.015) cm below the reference used for calibration, i.e. the metalling ring of the quartz dome covering the Brewer's diffuser (a schematic drawing of this reference can be found in González et al. (2023))".

- (1) Line 242: The statement referencing a "3%" drift lacks a time frame. Please specify the period over which this drift was observed.

(2) The term "drift" was used to describe the uncertainty of the radiometric stability. The reported values (of around 3 %) are the standard deviations from consecutive calibrations, as recommended by Bernhard and Seckmeyer (1999). The data used for this calculation were the available calibration records.

(3) To avoid confusion, the term "drift" has been replaced with "uncertainty" throughout the manuscript. Moreover, following the comments made by the referees, the following information has been added at the end of the indicated paragraph: "For Brewer #150, the radiometric uncertainty was derived using the yearly calibration files from 2005 to 2023, while for Brewer #185 the uncertainty was calculated using the monthly calibration files recorded from 2021 to 2024. As mentioned earlier, no data from prior years could be used as the entrance optics of Brewers #150 and #185 were replaced in 2005 and 2021, respectively".

- (1) Lines 252–253: The wavelength dependency of the stated effect should be included. Please indicate the specific wavelength used in this calculation.

(2, 3) The indicated phrase has been corrected to "a shift of less than 0.05 nm can produce an uncertainty in the UV irradiance of a few percent for wavelengths below 305 nm".

- (1) Lines 271–272: A formula should be included to clarify the described temperature dependence. Specify whether the linear relationship applies to raw count rates or their logarithms.

(2) The linear relationship refers to the responsivity of the instrument, i.e. the signal measured divided by the emitted irradiance of the reference lamp. Brewer #150 was characterised by placing 100 and 1000 W lamps. The instrument temperature increased gradually from 23 to 38 °C while it measured the irradiance emitted by the lamps. Then, the responsivity of the instrument was determined and its change with respect to the internal temperature was studied.

(3) To clarify this issue, the following formula and description has been added at the indicated lines: "Then, the relationship between the internal temperature of Brewer #150 and its change in responsivity with respect to a reference value (31 °C) was studied. The results showed that the instrument's responsivity decreases linearly with temperature, as:

$$r(\lambda, T) = r(\lambda, \mathrm{T_{ref}})[1 + \mathrm{c_T}(T - \mathrm{T_{ref}})]\,, \tag{2}$$

where $r(\lambda, T)$ is the responsivity measured at wavelength λ and internal temperature T, $r(\lambda, \mathrm{T_{ref}})$ is the responsivity measured at the reference temperature $\mathrm{T_{ref}}$ = 31 °C, and $\mathrm{c_T}$ is the slope of the linear fit. The latter is the temperature correction factor and for Brewer #150 it has a value of $\mathrm{c_T} = (-0.0016 \pm 0.0002)$ °C^{-1}".

- (1) Line 273: According to Eq. 9, the irradiance is divided by 1 + C(T – T_ref), not simply by the correction factor C.

(2, 3) Line 273 has been corrected to "Therefore, the UV measurements of Brewer #150 were corrected for temperature by considering this correction factor and the difference between the temperature of the UV scan and the reference temperature (31 °C), as indicated later in Eq. (9)".

- (1) Line 285: Avoid using the same variable name (C) for both the temperature and cosine corrections.

(2, 3) To avoid confusion, the temperature correction factor has been denoted as "$\mathrm{c_T}$" and the angular response as "$C_\mathrm{R}(\varphi, \theta, \lambda)$".

- (1) Lines 360–364: Describe how systematic error sources were treated for the Brewer instruments that lacked a full calibration.

  (2) Systematic error sources with no characterisation (such as cosine error or temperature dependence for some Brewer spectrophotometers) were not considered in the processing of UV measurements during the intercomparison campaign (Hülsen, 2023). As a result, the global irradiance ratio from these instruments (#117, #151, #172, #202, #228) to the QASUME showed larger deviations from unity than the one from Brewers with all corrections implemented (see the ratios found by Hülsen (2023)).

  (3) As mentioned in responses to comments 4b and 4c, this information has been added at the beginning of the discussion to clearly state that these Brewers have no cosine correction implemented and, as a result, their uncertainty evaluation is limited. Moreover, a comparison with the QASUME has been added to the results section to show that the instruments that lacked a full calibration perform worse than the fully calibrated Brewers.

- Line 372: A plot comparing the ratios between instruments should be included. These ratios should then be compared with the corresponding percentage uncertainties to assess the consistency of the results.

  (2, 3) The instruments have been compared using the ratio to the QASUME, the European reference. As discussed in the response to comment 4b, the agreement between all Brewer spectrophotometers is within 10 % from unity for wavelengths above 310 nm. Furthermore, the uncertainty of the ratio to the QASUME has also been determined, showing that only those Brewers with cosine correction include the ideal value of the ratio (unity) within their uncertainty interval.

- (1) Line 377: The sentence "the uncertainty increases as wavelength grows and SZA decreases" is highly misleading. While the absolute uncertainty may increase, the relative (%) uncertainty generally decreases.

  (2, 3) To clarify this issue, the term "absolute" has been added to differentiate between relative and absolute values. The indicated line has been corrected to "the absolute uncertainty increases as wavelength grows and SZA decreases". The Conclusions section has also been revised to ensure that the discussion regarding absolute and relative uncertainty values is unambiguous.

- (1) Figure 3 and Line 402: The fluctuations observed in the data from Brewers #158 and #151 should be discussed. If these variations are attributable to an outdated or inaccurate dispersion function, then why this function was not updated prior to the analysis?

  (2) The fluctuations of these instruments are indeed caused by wavelength misalignment. As mentioned earlier, the characterisation and uncertainty evaluation of the Brewer spectrophotometers have shown the current limitations of the Brewer network. One of these limitations is the one indicated by the referee: the dispersion function should be updated if fluctuations are detected. A complete and accurate QC procedure as the ones described by Webb et al. (1998) or Bernhard and Seckmeyer (1999) is currently beyond our abilities. However, only if the limitations are identified (i.e. improvement of stray light correction, inclusion of cosine correction, increasing the calibration frequency of the Brewer spectrophotometers, etc.), can they be overcome.

(3) A brief comment has been added to indicate that the discussion regarding wavelength shift is in section 4.3 as "The reason for these behaviours will be described later in section 4.3 (sensitivity analysis)". Furthermore, in the conclusions section the need for updated dispersion function has been added as follows: "Based on the findings of this sensitivity analysis, to reduce the overall uncertainty of a Brewer spectrophotometer, it is recommended to [...] (e) monitor wavelength shifts and reduce them below 0.05 nm through frequent wavelength calibrations and accurate determinations of the instrument wavelength scale".

- (1) Line 461: Clarify whether the term "error" or "uncertainty" is intended here. Also, please verify the stated values using the inverse square law.

(2) Line 461 can be confusing as it is comparing uncertainty and precision errors. Therefore, it is better to talk about the uncertainty associated with the distance alignment. As for the inverse square law, it was implemented in the Monte Carlo simulation to derive the alignment uncertainty. In each iteration, the distance was varied according to its uncertainty and the irradiance was recalculated as:

$$E'(\lambda) = E(\lambda) \cdot \left(\frac{\mathrm{d_r}}{d'}\right)^2,$$

where $E(\lambda)$ is the irradiance of the reference lamp, $\mathrm{d_r}$ is the reference distance (usually 500 mm for 1000 W lamps), d' is the sampled distance according to its uncertainty, and $E'(\lambda)$ is the resulting irradiance when the distance is modified.

Nevertheless, the results obtained using the Monte Carlo method can be compared to the GUM uncertainty framework, which propagates the distance uncertainty by obtaining the partial derivative of the inverse square law.

(3) The errors reported have been replaced with the uncertainties determined (0.59 mm for Brewer #150 and 0.58 mm for the remaining instruments). Moreover, the following discussion regarding the validity of the results obtained has been added to the manuscript: "According to Webb et al. (1998), if the nominal distance is d and its uncertainty u_d, the percentage uncertainty can be calculated using the inverse square law ($1/r^2$, where r is the distance between lamp and instrument) as $[(\mathrm{d} + u_\mathrm{d})^2 - \mathrm{d}^2] * 100 \,/\, \mathrm{d}^2$. Therefore, the previous results agree with the formula proposed by Webb et al. (1998)". Additionally, the calibration guidelines established by Webb et al. (1998) have also been mentioned in the sensitivity analysis in line 473 as: "This agrees with the recommendations of Webb et al. (1998). They suggest calibrating the instruments using three reference lamps".

- (1) Lines 518–520: The statement is misleading. Total ozone column (TOC) is typically derived from direct-sun observations, not from spectral UV irradiance measurements.

(2, 3) Following the comments made by all reviewers, the indicated paragraph has been deleted from the manuscript.

- (1) Lines 542–549: Ozone is only one of several atmospheric factors that influence long-term changes in UV irradiance. Other contributors can also introduce significant variability and trends.

(2, 3) Following the reviewer's general comment ("7. Section 5"), the indicated lines have been removed from the manuscript to shorten Section 5.

- (1) Line 622: Calibration should be conducted more frequently than once per year. Critically, it should be stated explicitly that the calibration lamps themselves must be periodically recalibrated, and up-to-date certificates must be used.

  (2) Indeed, the frequency of calibration should be higher than once a year. However, most of the Brewer spectrophotometers used in this study were calibrated once every two years. That is why in the conclusions section we emphasise it. As for the reference lamps, it should be stated that they also need to be periodically calibrated.

  (3) Following the reviewer's comment, the information regarding lamp calibration has been added in former line 622 as "(b) calibrate the reference lamps periodically to ensure up-to-date calibration certificates".

- (1) Lines 622–623: The cosine error should be characterized and corrected systematically. If uncorrected, replacing the diffuser could introduce a step-change in the time series data, undermining the consistency of long-term measurements.

  (2) Indeed, the cosine correction should be characterised and corrected on a regular basis. However, the results from this study show that the traditional optics lead to higher uncertainties than other entrance optics. Therefore, to reduce the overall UV uncertainty of a Brewer spectrophotometer, the traditional optics could be replaced. This will lead to a change in the responsivity of the instrument, but this doesn't have to affect long-term monitoring or UV trend calculation provided that the data is re-evaluated and its QC is revisited (e.g. https://doi.org/10.5194/acp-16-2493-2016).

  (3) The previous information has been added to the text as follows: "Although replacing the entrance optics will modify the responsivity of the instrument, this change will not affect the calculation of UV trends or long-term monitoring as long as the data is re-evaluated and its QC revisited (Fountoulakis et al., 2016a)".