



Evaluation of the uncertainty of the spectral UV irradiance measured by double- and single-monochromator Brewer spectroradiometers

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Abstract. Brewer spectroradiometers are robust, widely used instruments that have been monitoring global solar ultraviolet (UV) irradiance since the 1990s, playing a key role in UV research. Unfortunately, the uncertainties of these measurements are rarely evaluated due to the difficulties involved in the uncertainty propagation. This evaluation is essential to determine the quality of the measurements as well as their comparability to other measurements. In this study, eight double- and two single-monochromator Brewers are characterised and the uncertainty of their global UV measurements is estimated using the Monte Carlo method. This methodology is selected as it provides reliable uncertainty estimations and considers the nonlinearity of the UV processing algorithm. The combined standard uncertainty depends on the Brewer, varying between 2.5 % and 4 % for the 300–350 nm region. 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 %. These uncertainties arise primarily from radiometric stability, the application of cosine correction, and the irradiance of the lamp used during the instrument calibration. As the intensity of the UV irradiance measured decreases, dark counts, stray light (for single Brewers), and noise become the dominant sources of uncertainty. These results indicate that the overall uncertainty of a Brewer spectroradiometer could be greatly reduced by increasing the frequency of radiometric calibration and improving the traditional entrance optics.



1 Introduction

35 Brewer spectroradiometers (Brewer, 1973; Kerr, 2010) were initially developed in the 1970s for supplementing the ozone measurements of the Dobson spectrophotometer (Dobson, 1931). These first Brewers were single-monochromator spectrometers and are usually referred to as single Brewers. Towards the 1980s, they were modified to also measure solar ultraviolet (UV) irradiance (Bais et al., 1996). During this time, double-monochromator Brewers (also known as double
40 Brewers) were developed to reduce the stray light in UV measurements. Thanks to the robustness and stability of Brewer spectrometers, the early instruments continue in operation and the Brewer network has steadily increased in number. Today, more than 200 Brewers are deployed worldwide providing measurements of total ozone column (TOC), global UV irradiance, sulphur dioxide, aerosol optical depth in the UV, and nitrogen dioxide. All these measurements contribute to a better understanding of long-term UV variations (Fountoulakis et al., 2016; Simic et al., 2008; Smedley et al., 2012; Zerefos et al., 2012) and the dynamics of the Earth's atmosphere (Arola et al., 2003; Estupiñán et al., 1996; Fioletov et al., 1998).
45 Furthermore, Brewer spectral UV data have also been used to monitor the increase in surface UV-B levels due to the depletion of stratospheric ozone (Fioletov et al., 2001; Kerr and McElroy, 1993; Lakkala et al., 2003). Therefore, Brewer spectrophotometers have greatly contributed to the study of solar UV for more than 30 years.

To ensure the quality of Brewer UV measurements, quality assurance (QA) and quality control (QC) procedures must be performed. QA protocols are designed to characterise, calibrate, and compare the Brewer with other instruments. In Europe,
50 the QASUME unit is the reference spectroradiometer (e.g. Gröbner et al., 2010; Lakkala et al., 2008). While QA focuses on instrument performance, QC evaluates the uncertainty of the measurement by: (a) identifying the error sources, (b) determining the model that relates these sources with the output quantity (i.e. the UV irradiance), and (c) propagating the uncertainty using a numeric or analytical approach (e.g. Garane et al., 2006; González et al., 2023, 2024b). This is essential to determine the quality of the measurement and ensure its comparability to other measurements (BIPM et al., 2008a).
55 Unfortunately, for Brewer measurements, there is no consensus on how QA/QC should be performed and as a result, the data processing, uncertainty evaluation, and calibration practices vary from station to station. In this context, COST Action ES1207 EuBrewNet (European Brewer Network) is trying to harmonise and develop coherent practices for Brewer QA/QC (Redondas et al., 2018; Rimmer et al., 2018). All Brewers used in this study are part of EuBrewNet and as a result, their calibration and UV measurements are obtained following their protocols.

60 While EuBrewNet has a well-established QA for UV measurements, QC is a pending task. In fact, it remains one of the main challenges for Brewer sites measuring ozone (Fioletov et al., 2008). Although the main errors and uncertainties affecting spectral UV irradiance measurements are well-known (Bais, 1997; Bernhard and Seckmeyer, 1999; Webb et al., 1998), their proper characterisation is difficult and requires specialised equipment (such as tuneable lasers, portable unit systems, or devices to measure angular response) that is not available to most UV site operators. Furthermore, the calculation of the
65 uncertainty propagation is complicated due to the nonlinearity of the UV irradiance model.



Brewer sites performing QC for UV measurements usually approach the uncertainty propagation following the recommendations of the Guide to the Expression of Uncertainty in Measurement (GUM) (BIPM et al., 2008a). In particular, the GUM uncertainty framework (hereafter “GUF”) is applied by assuming that the UV irradiance model is linear (e.g. Garane et al., 2006). Although this assumption is valid for Brewer spectrometers, the GUF provides less accurate estimations than other uncertainty propagation techniques (González et al., 2024b), such as the Monte Carlo method (hereafter “MCM”) and the Unscented transformation (hereafter “UT”). The UT is an efficient technique that evaluates the uncertainty by applying the nonlinear model to a reduced set of points, referred to as sigma points (Julier et al., 1995; Julier and Uhlmann, 1997). These sigma points are carefully chosen using several parameters to ensure their statistics (first and second order) match those of the measurand. However, if these points are not selected properly, the UT fails to obtain a correct estimate and its corresponding uncertainty. While recommended values usually work, they may not be optimal in some cases (Straka et al., 2012; Turner and Rasmussen, 2010; Wang and Ding, 2020). Although the UT method provided accurate results for a specific double Brewer (González et al., 2024b), it is unclear whether those results can be extended to single Brewers and other double Brewers. Therefore, in this work the MCM was selected as it has a broader domain of validity than the UT and GUF, provided that a sufficient number of simulations are performed (usually 10^6 iterations) (BIPM et al., 2008b).

The original contribution of this article is the characterisation and uncertainty evaluation of ten single and double Brewer spectrometers (MkIV and MkIII type, respectively) using the methodology set by González et al. (2023). In this way, the MCM is implemented to evaluate the uncertainty of the Brewer UV network. Moreover, a sensitivity analysis has also been performed to examine the influence of every uncertainty source on each Brewer spectroradiometer. The UV scans used for the uncertainty analysis were recorded during the XVIII Intercomparison campaign of the Regional Brewer Calibration Center - Europe (RBCC-E) at El Arenosillo Observatory (37.1° N, 6.7° W, 41 m a.s.l., Huelva, Spain).

The paper is organised as follows. First, the specifications of single and double Brewer spectrophotometers as well as an overview of the intercomparison campaign are given in Section 2. Next, Section 3 describes the uncertainty evaluation, i.e. the characterisation of the uncertainty sources, the UV irradiance model, and the MCM approach. Then, in Section 4 the results obtained from the sensitivity and uncertainty analysis are discussed. Finally, Section 5 summarises the main conclusions of this study.

2 Instrumentation and data

2.1 Brewer spectroradiometers

In this study, the uncertainty of the spectral UV measurements performed by ten Brewer spectroradiometers have been evaluated. Two different types of Brewer spectroradiometers have been considered, MkIV (single monochromator) and MkIII (double monochromator). The serial number and information of each instrument is shown in Table 1.

The measuring procedure is similar for both Brewer types, i.e. global UV irradiance enters through the entrance optics and is redirected using a prism into the fore-optics. The incoming radiation is then focused, collimated, and its intensity adjusted



before entering the spectrometer, using quartz lenses and filter wheels. This spectrometer is a modified Ebert grating type that disperses the light into a spectrum using a diffraction grating. Finally, the photons are detected using a photomultiplier tube (PMT). A diagram of the MkIV and MkIII Brewers can be found in Kerr (2010) and González et al. (2023), respectively.

Table 1. Information for each Brewer spectrometer used in this study.

Brewer	Type (monochromator)	Operator	Institute (Country)
#117	MkIV (single)	José M. San Atanasio	State Meteorological Agency – AEMET (Spain)
#150	MkIII (double)	José M. Vilaplana	National Institute of Aerospace Technology (Spain)
#151	MkIV (single)	José M. San Atanasio	State Meteorological Agency – AEMET (Spain)
#158	MkIII (double)	Pavel Babal	OTT Hydromet (The Netherlands)
#172	MkIII (double)	Richard Kift	University of Manchester (UK)
#185	MkIII (double)	Alberto Redondas	Izaña Atmospheric Research Center, AEMET (Spain)
#186	MkIII (double)	José M. San Atanasio	State Meteorological Agency – AEMET (Spain)
#202	MkIII (double)	Nis Jepsen	Danish Meteorological Institute (Denmark)
#228	MkIII (double)	Nis Jepsen	Danish Meteorological Institute (Denmark)
#256	MkIII (double)	Alberto Redondas	Izaña Atmospheric Research Center, AEMET (Spain)

The difference between the two types of Brewers lies in the number of monochromators and the type of diffraction gratings. MkIV Brewers are single monochromators and the diffraction grating of the spectrometer is operated in the second order and has a line density of 1800 lines nm^{-1} . On the other hand, the spectrometer of MkIII Brewers consists of a pair of monochromators and gratings to reduce the stray light of the system. Both diffraction gratings have a line density of 3600 lines nm^{-1} and are operated in the first order (smaller diffracted angles than for double-monochromator Brewers).

The entrance optics for Brewer spectrometers consists of a Teflon diffuser covered by a quartz dome. Traditionally, the diffuser was flat, but the angular response of such an entrance optic can deviate substantially from the ideal cosine response (Bais et al., 2005; Lakkala et al., 2018). Therefore, new designs have been developed to improve the Brewer angular response (Gröbner, 2003). Brewer #150 has this novel entrance optic developed by CMS-Schreder (model UV-J1015) with a shaped teflon diffuser. On the other hand, Brewers #185 and #256 have a flat diffuser mounted on the CMS-Schreder optic. The remaining seven Brewers have the standard flat diffuser originally mounted in these spectrometers.

For spectral UV irradiance measurements, the operational wavelength range of the Brewers under study is 290–363 nm with a step of 0.5 nm. The shape of the slit function is triangular and the Full Width at Half Maximum (FWHM) ranges from 0.55 to 0.65 nm, depending on the instrument. Brewer spectrophotometers are operated within a weather-proof housing, but their internal temperature is not stabilised. The calibration and processing of the Brewer UV measurements under study are set by EuBrewNet and are described in the following sections.



120 2.2 Intercomparison campaign at INTA/El Arenosillo

The data used are the UV scans performed during the 18th Regional Brewer Calibration Center for Europe (RBCC-E) intercomparison held at El Arenosillo Observatory (37.1° N, 6.7° W, 41 m a.s.l.) in Huelva, Spain, from 5 to 15 September 2023 (WMO, 2023). All instruments were installed on the roof of the station, where the horizon is free up to 85° solar zenith angle (SZA).

125 The first days of the campaign, 6–10 September, were dedicated to assess the status of the participating Brewers (by comparing their ozone measurements with those of the reference, Brewer #185), to perform the necessary maintenance, and, finally, to gather data for the instruments' calibration. The angular characterisation and the UV comparison were carried out during the final days, 11–14 September. It should be mentioned that the angular response characterisation was performed for five MkIII Brewers (#150, #185, #186, #158, and #256). Three of them (#150, #186, and #256) were characterised using the
130 Brewer Angular Tester (BAT), described later in Section 3.1.3.

The protocol to measure global spectral UV irradiance consisted of scanning one UV spectrum from dawn to sunset every 30 minutes. The wavelength increment and time step were set to 0.5 nm and 3 s respectively. This setting was chosen to obtain simultaneous measurements between the 16 Brewer spectroradiometers (8 MkIII, 6 MkIV, and 2 MkII) participating in the campaign and the travelling reference QASUME (Gröbner et al., 2005; Hülsen et al., 2016) from the Physikalisch-
135 Meteorologisches Observatorium Davos/World Radiation Center (PMOD/WRC). The results from this intercomparison, along with other QASUME site audits, are published on the web page of PMOD/WRC (<https://www.pmodwrc.ch/en/world-radiation-center-2/wcc-uv/qasume-site-audits/>, last access: 2 February 2025).

In this work, the UV irradiances and the corresponding uncertainties of MkIII and MkIV Brewers (see Table 1) have been calculated using their raw UV counts, calibration files, slit functions, dead time, dark counts, reference lamp certificates, and
140 angular response measurements. This information is available at EuBrewNet (Rimmer et al., 2018) except for the lamp certificates and some calibration records, which were provided by the Brewer operators, Vladimir Savastiouk from International Ozone Services, and Gregor Hülsen from PMOD/WRC. In the following section, the UV processing algorithm and the uncertainty propagation techniques implemented are described.

3 Methodology

145 The combined standard uncertainty of the global UV irradiance measured by MkIII and MkIV Brewers has been calculated using a numerical propagation technique, the MCM. Furthermore, a sensitivity analysis has also been performed to identify the main sources of uncertainty in Brewer UV measurement procedure. To carry out the uncertainty evaluation, the uncertainty sources and the model relating these sources to the measured irradiance must be first characterised. In the absence of standard procedures for this task, the guidelines established by EuBrewNet have been followed. The uncertainty
150 sources and irradiance model are described in the following subsections.



3.1 Characterisation of the uncertainty sources

In this study, the uncertainty sources have been characterised following the methodologies of Bernhard and Seckmeyer (1999), González et al. (2023, 2024b), and Savastiouk et al. (2023). It should be noted that some of the sources considered in the uncertainty analysis could not be characterised as thoroughly as in those studies (such as noise, stray light, or radiometric stability). Nevertheless, the authors believe that this is preferable to ignoring those sources completely.

The uncertainty sources affecting the Brewer UV measurement procedure can be divided into three groups, depending on whether they affect (1) the counts measured by the instrument, (2) the radiometric calibration, or (3) the unprocessed irradiance.

3.1.1 Brewer counts

The counts measured by any Brewer spectrometer are affected by stray light, noise, dark counts, and dead time.

Stray light is the radiation coming from wavelengths other than the one being measured. This undesired light is able to reach the detector due to scatter inside the instrument and dust particles. The presence of stray light is larger in single Brewers (such as MkIV Brewers) and results in an overestimation of the measured global UV irradiance at short wavelengths (Bais et al., 1996; Davies, 1996). Therefore, EuBrewNet applies a correction only for single Brewers, as the stray light present in double Brewers is very low (Bais et al., 1996; Karppinen et al., 2015; Savastiouk et al., 2023). While this correction is implemented for ozone measurements (Redondas et al., 2018), for UV measurements further characterisation is needed. Currently, stray light is estimated as the number of counts recorded below 292 nm (e.g. Lakkala et al., 2008; Mäkelä et al., 2016) and then subtracted from the counts measured at all wavelengths. However, deriving the uncertainty of this method for the Brewers under study is difficult, as it would use the information from only five wavelengths (from 290 to 292 nm). Thus, the correction and the uncertainty estimation proposed by Savastiouk et al. (2023) were used to handle the stray light. This method calculates the stray light $S(\lambda)$ based on the raw counts recorded at 320 nm, $C_0(320 \text{ nm})$, using two coefficients

$$S(\lambda) = \begin{cases} \beta \cdot C_0(320 \text{ nm}), & \lambda < 310 \text{ nm} \\ \alpha \cdot C_0(320 \text{ nm}), & \lambda \geq 310 \text{ nm} \end{cases} \quad (1)$$

where α and β depend on the Brewer characteristics and can be determined using reference instruments with no measurable stray light (like the QASUME spectroradiometer). Then, the stray light obtained with Eq. (1) is subtracted from the raw counts at all wavelengths measured.

Since the single Brewers participating in the campaign had no stray light correction implemented, the typical values found by Savastiouk et al. (2023) were used as first guesses for the α and β coefficients. These values are deemed reliable as they studied over 20 single Brewers to derive them. Then, they were tuned by comparison with the spectral irradiance measured by the QASUME unit. For the two single Brewers of this study (#117 and #151), α was 0.4 %, while the coefficient β was 0.251 % for Brewer #117 and 0.223 % for Brewer #151.



The uncertainty of this method was evaluated by combining the uncertainty of (1) the raw counts recorded at 320 nm and (2) the α and β coefficients (Savastiouk et al., 2023). The first factor is dominated by noise and dark counts, which will be explained below. The uncertainty of the two coefficients was obtained using the estimations of Savastiouk et al. (2023) for their accuracy, repeatability and drifts in time. This analysis resulted in uncertainties of 0.008 % for both α and β .

185 Noise can be characterised by studying the signal-to-noise ratio (SNR) (e.g. Bernhard and Seckmeyer, 1999; Cordero et al., 2012). However, this ratio can only be determined if all conditions, such as the incoming radiation, remain stable. For CCD-array spectroradiometers, this is easy as the instrument can record several spectra in a few seconds. In contrast, Brewer spectroradiometers take approximately 5–6 minutes to measure a single UV spectrum. As a result, characterising the noise in Brewer measurements is only straightforward during the radiometric calibration, when the emitting lamp is stable. During
190 the RBCC-E campaign, the measurement of the irradiance of the reference lamp was acquired four times. With this information, the SNR for the radiometric calibration was calculated. Since it was proportional to the root of the raw counts recorded, the methodology proposed by Bernhard and Seckmeyer (1999) could be applied and the SNR for the counts measured under the Sun was obtained as:

$$SNR^S(\lambda) = SNR^R(\lambda) \sqrt{\frac{C_0^S(\lambda)}{C_0^R(\lambda)}}, \quad (2)$$

195 where $C_0^S(\lambda)$ and $C_0^R(\lambda)$ are the raw counts measured under the Sun and lamp (calibration), respectively, and $SNR^S(\lambda)$ and $SNR^R(\lambda)$ are the signal-to-noise of the outdoor and calibration measurements, respectively.

Dark counts are the counts recorded when no light is entering the instrument. Brewer spectroradiometers are programmed to measure the dark counts before every UV scan by blocking the incoming radiation. The dark counts of the Brewers under study increased as the internal temperature of the instrument rose. To estimate the uncertainty of the dark counts, the dark
200 counts measured at each temperature reached by the instrument were averaged and the corresponding standard uncertainty was calculated. The number of available measurements depended on the instrument, but all the Brewers under study recorded more than 40 dark counts measurements throughout the intercomparison campaign.

Dead time is the time after a photon has been recorded during which the photomultiplier tube (PMT) is unable to detect a second one. This causes the nonlinearity in Brewer response as any photons arriving during the dead time of the PMT are not
205 taken into account. Similarly to dark counts, dead time determination is also included in the schedule of Brewer spectrometers (DT test). Each instrument records it daily by measuring and comparing high and low intensities of an internal quartz-halogen 20 W lamp (standard lamp). Initially, the dead time of the instrument is stored in the B-files (instrument constants). Then, using the DT tests, this constant is frequently checked and updated when necessary. The dead time is characteristic of each Brewer as it depends on the type of PMT used. For the Brewers under study, the dead time varied from
210 25 to 36 ns and their uncertainties ranged from 0.3 to 3 ns. These values were derived from the constant files and the dead time tests carried out during the campaign.



3.1.2 Radiometric calibration

Brewer spectroradiometers were calibrated during the campaign, using one or two reference DXW-1000 W tungsten-
 215 filament incandescent halogen lamps. These lamps had been previously calibrated in various laboratories, ensuring their
 spectral irradiances are the ones stated in their calibration certificate when operated at the specified distance and electrical
 current. To ensure the latter, the radiometric calibration was performed with a mobile system that places the lamp on top of
 the Brewer diffuser at the required distance. This setup also stabilised and monitored the electrical current at its nominal
 value using a multimeter. Therefore, the main sources of uncertainty of Brewer radiometric calibration are produced by the
 220 distance adjustment (between the lamp and the diffuser), the radiometric stability, and the spectral irradiance emitted by the
 reference lamp. Small fluctuations in the electrical current of the lamp can also produce errors in the calibration. However,
 this source could not be included in the Monte Carlo simulation, as it requires the determination of the lamp's operating
 temperature (Schinke et al., 2020) and this could not be carried out during the campaign.

In the RBCC-E campaigns hosted at El Arenosillo, the distance between the plane of the reference lamp and the Brewer's
 225 diffuser is adjusted using a ruler with a precision of 1 mm. Since 1000 W lamps are usually placed at 50 cm, for most Brewer
 spectrometers, the lamps were set at (500 ± 1) mm. The exceptions are Brewers #158 and #150, their lamps were set at (413 ± 1) mm and (500.0 ± 0.6) mm, respectively. The reference lamp used to calibrate Brewer #158 needed to be placed at 412.5 mm, as indicated in its calibration certificate. Brewer #150, on the other hand, has an additional source of uncertainty since the position of its diffuser's reference plane needs to be determined as well (González et al., 2023).

230 Regarding the uncertainties of the irradiances of the reference lamps, there is no need to determine them since all lamps used
 during the campaign had been previously calibrated in different standard laboratories. Therefore, their emitted irradiances
 and their corresponding expanded uncertainties (coverage factor of $k = 2$) are specified in their calibration certificates. These
 uncertainties depend on the lamp and the wavelength, slightly decreasing from 2–3 % at 290 nm to 1–2 % at 360 nm.

Even if a Brewer spectroradiometer is regularly calibrated, the responsivity of the instrument varies with time. This drift is
 235 caused by several factors such as transportation, storage, and ageing of the instrument as well as the instability of the
 photomultiplier tube (PMT). To characterise the radiometric stability of every Brewer, the standard deviation of the
 differences between consecutive calibration factors has been calculated, as suggested by Bernhard and Seckmeyer (1999).
 However, long calibration records are needed to derive a reliable standard deviation in this manner. Unfortunately, not all
 Brewers studied had enough calibration files. Some of them had been operating for less than 2 years, others had undergone
 240 several modifications that greatly affected their responsivity (such as replacement of the PMT or change of entrance optics),
 and the rest were not calibrated frequently enough. As a result, Brewers #150 and #185 were the only ones characterised
 following the methodology of Bernhard and Seckmeyer (1999). For the remaining instruments, a 3 % drift was assumed as
 several Brewer spectroradiometers (both double and single) exhibit drifts of that order (Garane et al., 2006; Lakkala et al.,
 2008). This value is also similar to the average drifts found for Brewers #150 and #185, of 2.9 % and 2.4 %, respectively.



245 3.1.3 Raw irradiance

Even if error sources affecting the counts and the radiometric calibration are characterised (as indicated in the sections above), there are still some uncertainty sources affecting the raw irradiance. Specifically, wavelength misalignment, temperature dependence, and cosine error.

Wavelength misalignment refers to a mismatch between the wavelength desired and the one being measured. It is usually
 250 corrected by determining the wavelength shift for every wavelength measured. Although this shift is small for Brewer spectroradiometers, it still leads to important errors, especially in the UV-B (280–315 nm) due to the marked decline in the solar irradiance at this region. For instance, a shift of less than 0.05 nm can produce an uncertainty in the UV irradiance of a few percent (Bais, 1997, González et al., 2024b).

Wavelength shifts can be determined using specific software like SHICrvm (Slaper et al., 1995) or MatSHIC (Hülsen et al.,
 255 2016). There are other options (as explained by Bernhard and Seckmeyer (1999)), but this one is the most straightforward and these detection algorithms also derive a shift for every wavelength and irradiance level measured. In this study, the wavelength shifts were obtained using SHICrvm as it is the algorithm implemented in EuBrewNet. These shifts were also estimated during the RBCC-E campaign and can be checked in the report elaborated by the PMOD/WRC (available at https://www.pmodwrc.ch/wcc_uv/qasume_audit/reports/2023_09_spain_INTA_RBCCE18.pdf, last access: 2 February
 260 2025). Furthermore, there is a second contribution to the wavelength misalignment, the precision of the micrometre, i.e. the system setting the wavelengths measured by a Brewer spectroradiometer. This precision is approximately 8 pm (Gröbner et al., 1998).

Brewer spectrometers, no matter the type, have no temperature stabilisation system. Thus, the internal temperature fluctuates throughout the day, resulting in a temperature dependency in Brewer global UV measurements. This fact is well-documented
 265 (Fountoulakis et al., 2017; Garane et al., 2006; Lakkala et al., 2008; Weatherhead et al., 2001), but there is no standard methodology for its characterisation. Therefore, EuBrewNet lets the Brewer operators characterise this source in the way they see fit. As a recommendation, the work of Lakkala et al. (2008) is indicated.

No temperature characterisation was performed during the campaign. As a result, this uncertainty source was only included in the uncertainty evaluation of Brewer #150. This instrument was characterised on three separate days in 2022, using 100
 270 and 1000 W lamps. The instrument temperature increased gradually from 23 to 38 °C while it measured the irradiance emitted by the lamps. The results showed that its dependency on temperature is linear, with a correction factor of $C = (-0.0016 \pm 0.0002) ^\circ\text{C}^{-1}$ (González et al., 2023). Therefore, the UV measurements of Brewer #150 were corrected by dividing the irradiance values by this factor, as indicated later in Eq. (9).

The angular response of a Brewer spectroradiometer deviates considerably from the ideal angular behaviour. This deviation
 275 is mainly caused by imperfections in the entrance optics and is called cosine error, after the ideal behaviour. For single Brewers, the cosine error varies between 8 and 12 % (Bais et al., 2005; Garane et al., 2006), while for double Brewers it ranges between 4–11 % (Antón et al., 2008; Bais et al., 2005; Lakkala et al., 2018). Although cosine correction is one of the



most important uncertainty sources (Garane et al., 2006; González et al., 2024b), it is rarely characterised in RBCC-E campaigns (e.g. Lakkala et al., 2018). During the 18th RBCC-E campaign, five MkIII Brewer spectroradiometers characterised their angular response error. For this selection of Brewers, the cosine correction factor was calculated as (Gröbner et al., 1996)

$$f_g = f_d \left(1 - \frac{DIR}{GLO}\right) + f_r \frac{DIR}{GLO}, \quad (3)$$

where f_d and f_r are the diffuse and direct cosine errors respectively, f_g the cosine correction factor, and DIR and GLO the direct and global irradiances.

In Eq. (3), $f_r = C(\varphi, \theta, \lambda) / \cos \theta$, where $C(\varphi, \theta, \lambda)$ is the angular response of the Brewer diffuser. For most Brewers, this was measured using the Brewer Angular Tester (BAT), which measures the North-South and West-East planes using a 150 W Xe lamp placed at fixed angles (from -85° to 85° by steps of 5°). The standard uncertainty of the direct cosine error was derived from repeated measurements of Brewer #150, resulting in values varying from 0.002 at 5° to 0.006 at 85° .

The diffuse cosine error was estimated integrating numerically the angular response $f_d = \frac{1}{\pi} \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} C(\varphi, \theta, \lambda) \sin \theta d\theta d\varphi$.

This factor is specific for each instrument, for the Brewers studied it ranged from 0.908 (Brewer #186) to 0.986 (Brewer #150). Its uncertainty was estimated as indicated by Bernhard and Seckmeyer (1999), based on the findings of Gröbner et al. (1996).

$$u(f_d) \approx \frac{|1-f_d|}{|1-f_d^G|} \Delta D^G, \quad (4)$$

where f_d^G is 0.883 (the diffuser error found by Gröbner et al. (1996)) and ΔD^G is the difference found by Gröbner et al. (1996) between f_d^G and the diffuse error derived when a homogenous sky radiance distribution is not assumed.

Finally, the ratio DIR/GLO was calculated using the radiative transfer model libRadtran (Emde et al., 2016) for a variety of SZAs. Other inputs to the model were the average Angström's turbidity coefficient (0.039) and Angström's exponent (1.371) derived from the El Arenosillo CIMEL measurements and mean TOC recorded by Brewer #150 during the campaign (295 DU), as well as the surface albedo (0.05), determined with a Li-Cor spectroradiometer. The uncertainty of this quantity at every SZA was estimated from all ratios measured within the desired SZA 1° (angular variability).

3.2 UV irradiance model

Spectral UV irradiance measured at wavelength λ was obtained following the standard processing of EuBrewNet, except for those Brewer with stray light and cosine correction. These two uncertainty sources were estimated using different methodologies, since the ones currently implemented in EuBrewNet could not be easily included in the Monte Carlo simulation. The processing algorithm entails a series of corrections as the UV irradiance measured is affected by several error sources (see Section 3.1.). The first step is to correct the raw counts registered $C_0(\lambda)$ for stray light, dark counts, and dead time (UV level 1 in EuBrewNet).



Stray light is calculated using Eq. (1) and is then subtracted from the raw counts (only for single Brewers)

$$C_1(\lambda) = C_0(\lambda) - S(\lambda). \quad (5)$$

310 Then, dark counts and dead time are corrected according to the practices established by the manufacturer (Kipp & Zonen, 2015). Dark counts are simply subtracted from the UV counts

$$C_2(\lambda) = C_1(\lambda) - D, \quad (6)$$

where $C_1(\lambda)$ are the counts corrected for stray light and D the dark counts.

On the other hand, dead time is corrected iteratively ($n = 1 \dots 10$) by assuming Poisson statistics:

$$315 \quad C_3(\lambda, n + 1) = C_2(\lambda) \cdot \exp(\tau C_3(\lambda, n)). \quad (7)$$

In Eq. (7), $C_2(\lambda)$ is the observed count rate (corrected for dark counts and stray light) at wavelength λ , τ the dead time, and $C_3(\lambda)$ the true count rate. As a first guess, $C_3(\lambda, 1) = C_2(\lambda)$.

Then, the raw irradiance $E_0^M(\lambda)$ is obtained by dividing the corrected count rates by the response of the instrument:

$$E_0^M(\lambda) = \frac{C_3^M(\lambda)}{r(\lambda)}, \quad (8)$$

320 where $C_3^M(\lambda)$ are the corrected counts (stray light, dark counts, and dead time) measured outdoors, and $r(\lambda)$ the responsivity of the Brewer. The latter is determined by performing a radiometric calibration, (see Section 3.1.2).

The resulting UV irradiances need further processing to correct the temperature dependence, wavelength shifts, and cosine error.

First, they are corrected for temperature dependence by assuming a linear relationship:

$$325 \quad E_1^M(\lambda) = \frac{E_0^M(\lambda)}{1 + C(T - T_{\text{ref}})}, \quad (9)$$

where $E_0^M(\lambda)$ is the raw irradiance measured at wavelength λ , $E_1^M(\lambda)$ is the irradiance corrected for temperature, C is the temperature correction factor, and T_{ref} is the reference temperature.

Secondly, the cosine correction is carried out using the methodology set by Gröbner et al. (1996). This derives a correction factor for each wavelength measured using Eq. (3) and corrects the irradiance by:

$$330 \quad E_2^M(\lambda) = E_1^M(\lambda) / f_g(\lambda, \theta), \quad (10)$$

where $E_1^M(\lambda)$ is the irradiance corrected for the temperature dependence, $f_g(\lambda, \theta)$ the cosine correction factor, and $E_3^M(\lambda)$ is the corrected irradiance for temperature and cosine error.

Finally, the irradiance is further corrected for the wavelength shifts using the SHICrvm software (Slaper et al., 1995). To limit the SZA (SZAs smaller than 90°), in this study only the irradiances measured between 06:30 and 18:00 UT were

335 corrected.



3.3 Monte Carlo method

The Monte Carlo method estimates the uncertainty of the measurement by propagating the distribution of the input quantities, i.e. the uncertainty sources. These are determined by drawing from the probability density function (PDF) of the error sources. In this study, two types of PDFs have been considered: gaussian and rectangular. Following the recommendations of the GUM, gaussian distributions are assigned to those variables that can be characterised by a best estimate and a standard uncertainty, such as dead time, dark counts, or noise. On the other hand, rectangular distributions are appropriate for those sources that are best described by a lower and upper limit, i.e. the probability that the true value of the variable lies within the fixed interval is constant and is zero outside this interval. This is the case for the distance adjustment or the wavelength shift variables.

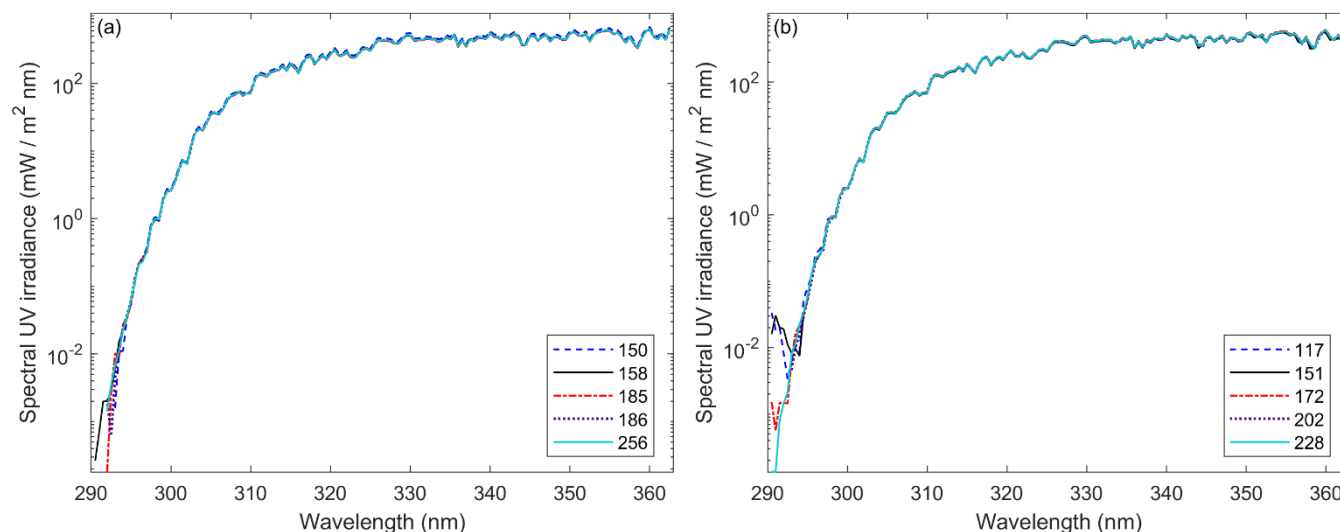
Once the distributions are known, the MCM can be implemented. To carry out this task, the number of times the model will be evaluated (Monte Carlo trials, M) must be first selected. In this study, $M = 10^6$ since this value is expected to deliver a 95 % coverage interval for the spectral irradiance (BIPM et al., 2008b). Then, at every trial, the uncertainty sources are varied according to their PDFs, forming a M vector for every source. For each of the M draws, the irradiance model is evaluated, obtaining a M vector of the output irradiance. Then, the average and the standard deviation of these irradiances are taken as the best estimate and its standard uncertainty, respectively.

The procedure described above is the one implemented to calculate the combined standard uncertainty. However, the MCM can also estimate the contribution of each uncertainty source to the total uncertainty budget. This is performed by running the M trials while varying only one uncertainty source and fixing the rest at their best estimate (BIPM et al., 2008b). In this way, the dominant uncertainty sources can be identified.

4 Results

The uncertainty evaluation was performed for all scans measured during the campaign. However, the results obtained were very similar in all cases. Therefore, only the estimations corresponding to 13 September 2023 are shown in this section. This day was selected as most Brewers measured uninterruptedly (no maintenance or calibrations were performed) and under cloud-free conditions.

To present the results, the Brewers studied have been separated into two groups. The first group includes the five Brewers whose angular responses were characterised (#150, #158, #185, #186, and #256). The remaining five Brewers were gathered in a second set as their characterisation is less elaborated. Therefore, the second group has two single (#117 and #151) and three double (#172, #202, and #228) Brewers.



365 **Figure 1: Spectral UV irradiance recorded at 14:00 UTC on 13 September 2023 by all the Brewer spectroradiometers studied. (a) First group formed by double Brewers with cosine correction (#150, #158, #185, #186, and #256). (b) Second group formed by two single (#117 and #151) and three double Brewers (#172, #202, and #228) with no cosine correction.**

Figure 1 illustrates one of the UV spectra recorded on 13 September 2023. This will help understand the behaviour of the combined standard uncertainty presented in the following section. As can be seen from Fig. 1, the spectral UV irradiance increases rapidly between 290 and 310 nm (due to the decrease of the ozone absorption). Then, from 315 nm onwards, it levels off. Furthermore, there is good agreement between all the Brewers between 310 and 360 nm. For wavelengths shorter than 300 nm, the single Brewers (#117 and #151) are unable to measure UV irradiance with the same precision as the double monochromator instruments.

375 **4.1 Combined standard uncertainty**

The combined standard uncertainty of all Brewer spectrometers depended on the wavelength and the solar zenith angle (SZA), displaying the same behaviour as the spectral UV irradiance (see Fig. 1). That is, the uncertainty increases as wavelength grows and SZA decreases. As an example, Fig. 2 shows the absolute combined standard uncertainties of the UV irradiances measured on 13 September 2023 at 14:00 UTC (40° SZA). The scale presented is logarithmic to highlight the differences between the Brewers at short wavelengths. Below 300 nm, the differences between double and single Brewers increase greatly, with single Brewers (#117 and #151) having uncertainties that at least triple those of double Brewers. This was expected as single Brewers are affected greatly by stray light and its effect is more pronounced in the UV-B region. On the other hand, there are slight variations between the uncertainties of double Brewers, mostly caused by (a) dark counts and noise at short wavelengths and (b) dead time and cosine correction at larger wavelengths. The influence of these uncertainty sources will be studied in the following section (sensitivity analysis).

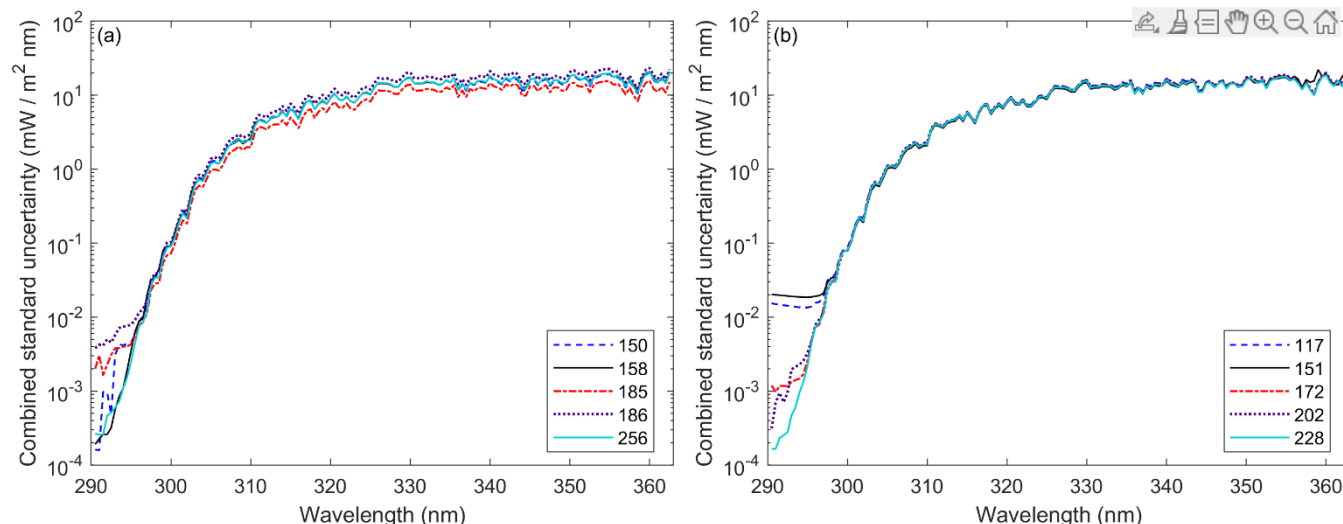


Figure 2. Combined standard uncertainties of the UV irradiances presented in Fig. 1. (a) First group (double Brewers with cosine correction). (b) Second group (two single and three double Brewers with no cosine correction implemented).

To better understand the magnitude of the combined standard uncertainty, it is interesting to study its relative values. The relative combined standard uncertainty (the absolute combined standard uncertainty divided by the UV irradiance measured) displayed different behaviours with wavelength and SZA depending on the instrument. For most Brewers, the relative uncertainty values ranged from 2.5 % to 4 % for wavelengths between 300 and 360 nm and showed no SZA dependency.

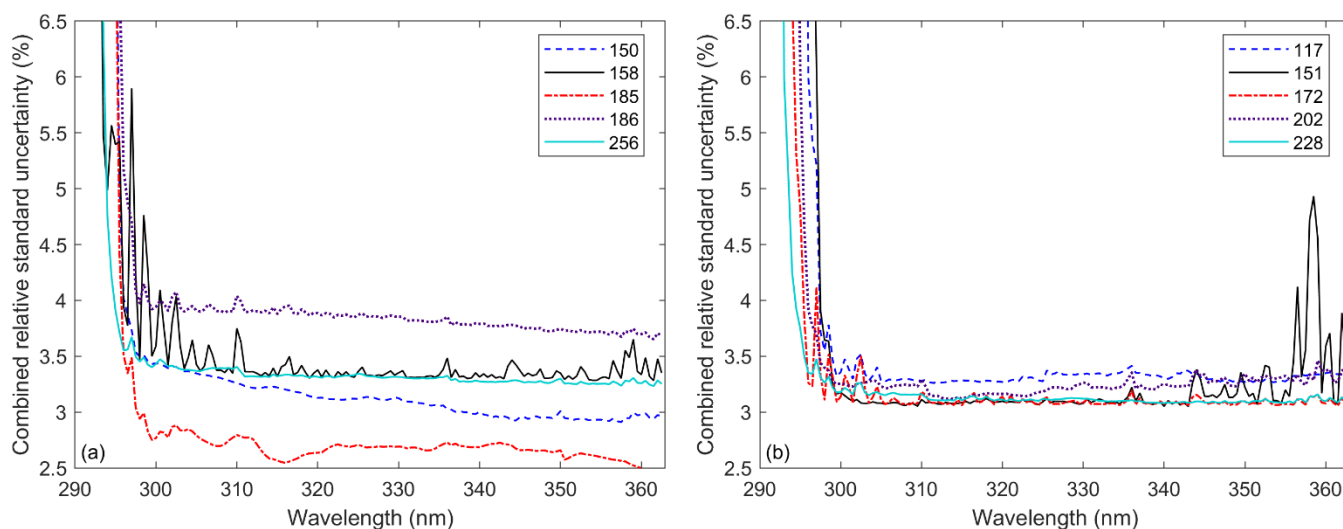


Figure 3. Relative combined standard uncertainties of the UV irradiances shown in Fig. 1. (a) First group (double Brewers with cosine correction). (b) Second group (two single and three double Brewers with no cosine correction implemented).

To illustrate the wavelength dependency, the relative uncertainties of the UV scan performed on 13 September 2023 at 14:00 UTC (40° SZA) are shown in Figure 3. It should be noted that the relative uncertainties of all Brewers increase significantly



below 300 nm as the UV irradiances measured are very small, close to $0 \text{ W m}^{-2} \text{ nm}^{-1}$. Between 300 and 360 nm, the relative combined standard uncertainty of some Brewer spectrometers (a) decreases slightly with wavelength (#150 and #186), (b) increases gradually with wavelength (#202), (c) fluctuates significantly (#158 at short wavelengths and #151 at large wavelengths), and (d) is approximately constant (#117, #172, #185, #228, and #256).

Regarding the angular dependency, Figure 4 represents all the relative uncertainty values derived on 13 September at 335 nm. This wavelength was selected to minimise the effect of the fluctuations found for Brewers #151 and #158 (see Figure 3). Figure 4 shows that the relative combined standard uncertainty of most Brewers (#117, #150, #151, #172, #228) has no angular dependency. On the other hand, the relative uncertainties of the remaining Brewer either increase (first group except for #150) or slightly decrease (#202) with SZA.

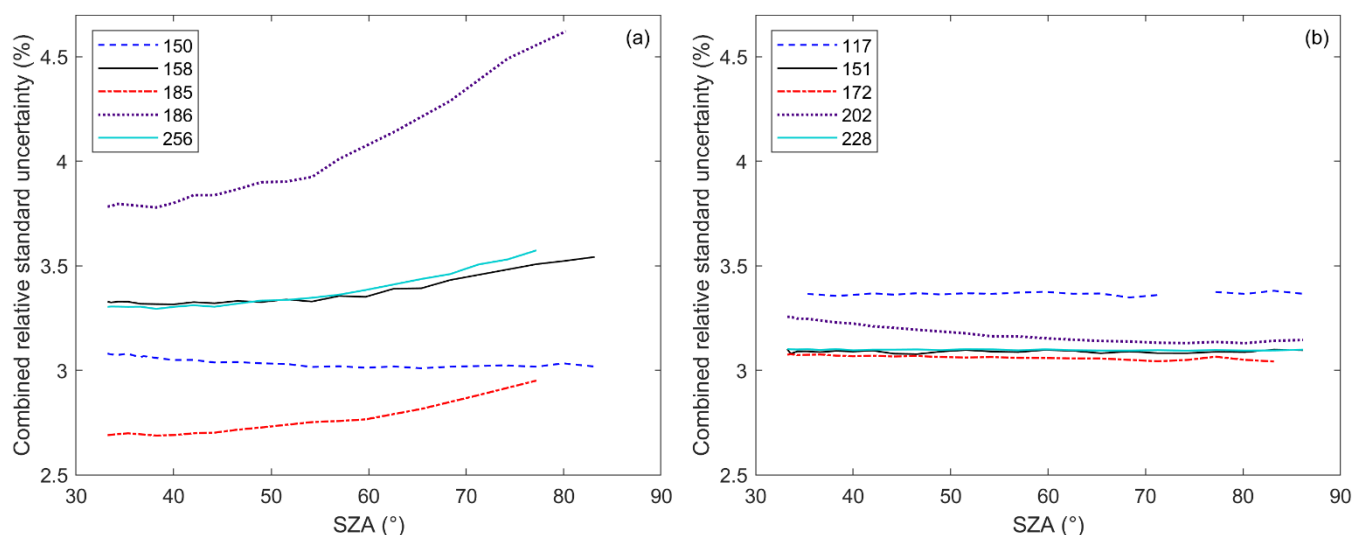


Figure 4. Relative combined standard uncertainties of all UV irradiances measured on 13 September 2023 at 335 nm. (a) First group (double Brewers with cosine correction). (b) Second group (two single and three double Brewers with no cosine correction implemented).

To clarify which uncertainty sources are responsible for the different behaviours found for each Brewer, a sensitivity analysis has been performed.

4.2 Sensitivity analysis

Generally, for wavelengths above 300 nm, the dominant uncertainty sources are radiometric stability, cosine correction (if implemented), and the irradiance of the reference lamp. As an example, a summary of the sensitivity analysis is shown in Fig. 5 for a single (#117) Brewer and Fig. 6 for a double (#185) Brewer spectrometer. As the intensity of the incoming UV radiation decreases, i.e. as wavelength decreases and SZA rises, dark counts, noise, and stray light (if the Brewer is a single monochromator) begin to gain influence. In fact, for wavelengths below 295 nm, they become the dominant sources (see Figs. 5 and 6). However, there were exceptions to this behaviour (mainly Brewers #117, #151, #158, and #202), showing



that dead time, noise, and wavelength shift can also become dominant uncertainty sources in the UV-A region (315–400 nm). In the following, the influence of each uncertainty source on the total uncertainty budget will be described in greater detail.

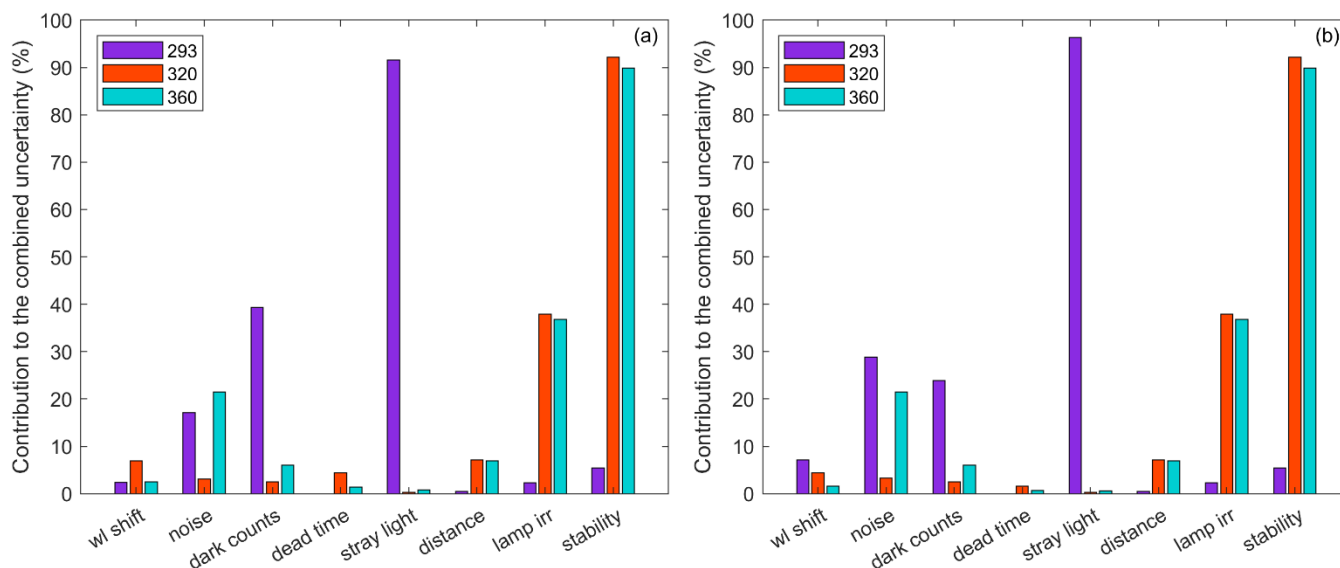


Figure 5. Relative contribution of the uncertainty sources of a single monochromator Brewer (#117) to the combined standard uncertainty of the UV spectrum measured on 13 September 2023 at three wavelengths (293, 320, and 360 nm) and two SZAs, (a) 35° and (b) 63°.

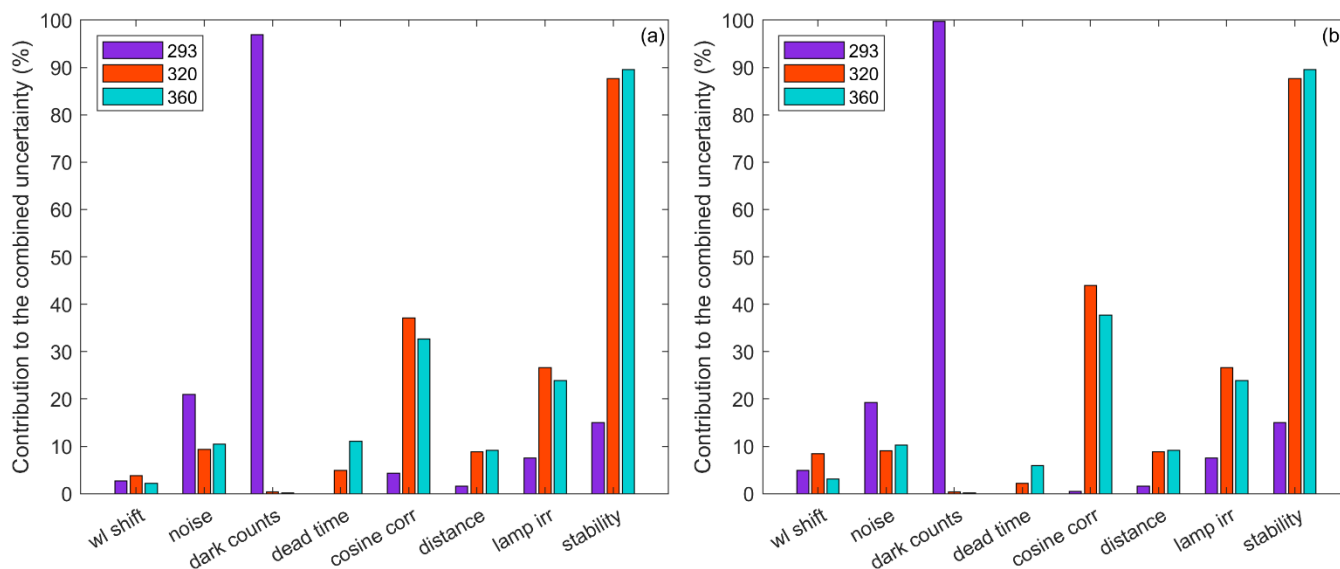


Figure 6. Relative contribution of the uncertainty sources of a double monochromator Brewer (#185) to the combined standard uncertainty of the UV spectrum measured on 13 September 2023 at three wavelengths (293, 320, and 360 nm) and two SZAs, (a) 33° and (b) 63°.



4.2.1 Noise

435 For most Brewers, the uncertainty produced by noise was most dominant (second or third most influential source of uncertainty) for wavelengths below 300 nm. At larger wavelengths, above 310 nm, noise loses influence, resulting in an uncertainty of less than 0.6 % in the UV irradiance measured, regardless of the intensity of the incoming radiation. Brewer #117 was an exception, with a SNR of 0.1, noise led to uncertainties of up to 0.9 %. In this case, noise was the third most dominant source for wavelengths larger than 330 nm (see Fig. 5).

440 4.2.2 Dark counts

The uncertainty contribution due to dark counts was important solely at wavelengths smaller than 295 nm. For larger wavelengths, its contribution can be disregarded as dark counts correction leads to irradiance uncertainties of less than 0.03 % in double monochromator Brewers. It is interesting to note that single Brewer spectroradiometers showed larger dark counts contributions. For example, for wavelengths above 310 nm, dark counts caused irradiance uncertainties of 0.3 %.

445 These two Brewers (Brewers #117 and #151) recorded during the campaign larger dark counts than those of double Brewers. As a result, the standard deviation obtained is greater as well (see Section 3.1.1), resulting in a larger contribution.

4.2.3 Stray light

Stray light was only considered for single monochromator Brewers, i.e. Brewers #117 and #151. The sensitivity analysis shows that the contribution of stray light increases rapidly as wavelength decreases. Furthermore, it also increases with SZA

450 as shown in Fig. 5. For single Brewers and at wavelengths below 300 nm, stray light was the dominant source, accounting for 95 % of the total uncertainty budget.

4.2.4 Dead time

Dead time contribution increases with the number of counts recorded, i.e. as SZA declines and wavelength rises. Most of the Brewers used in this study have an uncertainty of 1 ns in their dead time, which results in a maximum uncertainty in the irradiance measured of 0.2 % at 68° SZA and 0.8 % at 33° SZA. Therefore, the contribution of dead time is not dominant

455 and only becomes significant as SZAs decrease (fourth or fifth most influential source). However, this is not true for larger dead time uncertainties, as is the case of Brewer #202. Since its dead time uncertainty is 3 ns, the maximum uncertainty produced in the irradiance measured is 0.8 % at 57° and 1.5 % at 33°. This larger uncertainty is likely caused by the replacement and voltage adjustment of the standard lamp during the RBCC-E campaign (WMO, 2023). Thus, for this

460 Brewer the dead time is the second most influential uncertainty source for wavelengths larger than 320 nm.



4.2.5 Distance adjustment

An error of 1 mm when placing the reference lamp at 500 mm results in a 0.23 % uncertainty in irradiance. On the other hand, Brewers #150 and #158 display slightly different results, as their reference lamps were placed at 413 mm and 497.7 mm, respectively (see Sect. 3.1.2). For these Brewers, the distance adjustment leads to uncertainties of 0.24 % (#150) and 0.28 % (#158). It should be noted that all uncertainty sources involved in the calibration of the instrument (distance, irradiance of the reference lamp, and radiometric stability) have no angular dependency. As they only affect the responsivity of the instrument, they have the same influence on all UV measurements as shown in Eq. (8).

4.2.6 Irradiance of the reference lamp

The irradiance of the 1000 W lamps used during the calibration is the second most dominant uncertainty source in the UV-A region. The irradiance uncertainty depends on the lamp used and the wavelength measured, ranging from 0.6–1.4 % at 290 nm to 0.4–1.2 % at 360 nm. The Brewer spectroradiometers least affected by this uncertainty source had been calibrated using two reference lamps during the intercomparison campaign. Therefore, the overall uncertainty of a Brewer spectrometer can be reduced by calibrating the instrument with more than one reference lamp.

4.2.7 Radiometric stability

Radiometric instability is the dominant uncertainty source for all Brewer spectroradiometers, for wavelengths larger than 300 nm (see Figs. 5 and 6). For most Brewers, the uncertainty caused by instability was 3 %. This was expected, since, for most Brewers, a reliable stability drift could not be derived and, as a result, a 3 % drift was assumed (in agreement with the findings of Garane et al. (2006) and Lakkala et al. (2008)). Brewers #150 and #185 had their instability characterised and reported uncertainties of up to 3.6 % and 2.5 %, respectively. Brewer #150 is calibrated yearly using 1000 W lamps, while Brewer #185 is calibrated approximately every 2–3 months using 200 W lamps and yearly with 1000 W lamps. Therefore, calibrating frequently is recommended to reduce the instrument's combined standard uncertainty.

4.2.8 Wavelength shift

Wavelength shifts were responsible for the rapid fluctuations of the relative uncertainties of Brewers #151 and #158 (see Figure 2). The spikes were larger for Brewer #151 as the wavelength shifts of this instrument, for wavelengths above 350 nm, were 10 times larger than the ones of the other Brewers. For Brewer #151, a wavelength shift of 0.12 nm at 355 nm resulted in a relative uncertainty of 4 %, becoming the dominant uncertainty source at this region. This is interesting as it shows the influence wavelength shifts can have on the UV-A irradiance measured. On the other hand, Brewer #158 has shifts of 0.05 nm, resulting in a 1 % uncertainty in the irradiance for wavelengths between 310 and 360 nm.



For the remaining Brewers, the contribution of wavelength shift is negligible for wavelengths above 300 nm (less than 0.3 %). At shorter wavelengths, shifts of 0.03 nm can produce up to 20 % irradiance uncertainty. Nevertheless, they are not a dominant uncertainty source regardless of the wavelength and SZA measured (see Figs. 5 and 6).

4.2.9 Temperature correction

Although temperature correction has an important effect on the UV irradiance measured, it has no significant contribution to the overall uncertainty of Brewer #150. In fact, it leads to an irradiance uncertainty of less than 0.2 % for SZAs below 75°. However, since the dependency with temperature is specific for each instrument (Fountoulakis et al., 2017), different results may be found for other Brewers.

4.2.10 Cosine correction

As mentioned earlier, this uncertainty source could only be studied for Brewers #150, #158, #185, #186, and #256, as they are the only ones with a characterised angular response. Figure 7 shows that cosine correction has a great impact on most Brewers, with an average contribution that ranges from 0.4 % (#150) to 1.9 % (#186) at 33° SZA. Brewer spectrometers #158, #185, and #256 present an intermediate situation, with a contribution of around 1.4 %. These differences are likely due to the entrance optics. Brewers #185, #186, #256, and #158 have a flat diffuser, while Brewer #150 has a shaped diffuser. Furthermore, this contribution increases gradually with SZA for all Brewers except #150. Consequently, this uncertainty source is responsible for the increase of the relative combined uncertainty standard with SZA observed in Fig. 3a.

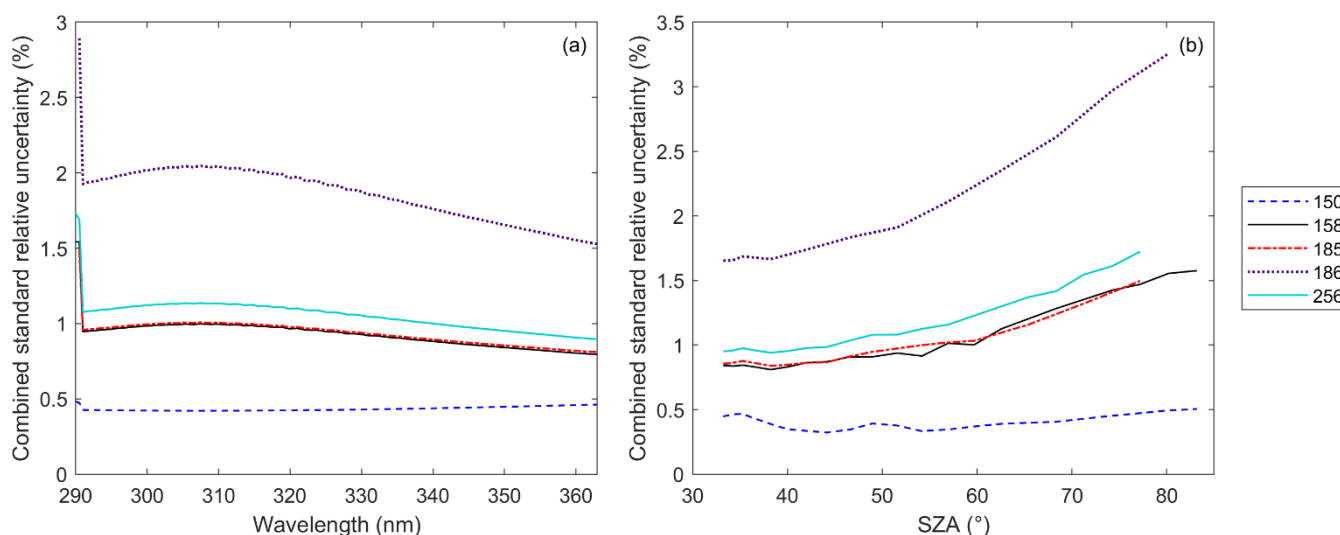


Figure 7. Combined standard relative uncertainty on 13 September 2023 caused by the cosine correction implemented. (a) Spectral dependency at 12:30 UTC. (b) SZA dependency at 350 nm.



For Brewer spectroradiometers #158, #185, #186, and #256, cosine correction is the second most important uncertainty source for wavelengths larger than 300 nm, regardless of the SZA. For Brewer #150, thanks to its improved angular response, this source has less impact, being the third most influential uncertainty source for SZAs larger than 50°.

5 Applications of Brewer uncertainty evaluation

This study provides an accurate and precise quantification of the uncertainty in spectral measurements of solar radiation using Brewer spectroradiometers. It also identifies the main sources of this uncertainty and quantifies their individual contribution to the combined standard uncertainty, pointing out the main areas for improvement in the instrumentation and calibration processes. These aspects are of great interest for different studies and fields of work.

One of the key applications of an accurate quantification of the uncertainty in spectral measurements of solar UV radiation is the precise estimation of the total ozone content (TOC) in the atmosphere column (Fioletov et al., 2005). Ozone is the primary modulator of the UV solar radiation that reaches the Earth's surface and is suffering a recovery process since 2000, after its dramatic depletion in the 1980s due to anthropogenic emissions of chlorine and bromine compounds, particularly chlorofluorocarbons (CFCs) (Solomon et al., 2016). Current research studies focus on detecting signs of recovery and determining the minimum detectable trend from ozone measurements provided by Brewer spectroradiometer, which is estimated to be around 1% per decade (Bodeker and McElroy, 2000; Kerr and McElroy, 1993; WMO, 2018). A precise determination of the measurement uncertainty will reduce the uncertainty in conclusions about the existence of these trends.

Another important application 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). It is crucial to assess the spectral measurement uncertainty at each wavelength, as the resulting overall uncertainty can significantly vary depending on the biological action spectrum used for weighting and integration.

For the ten Brewer spectroradiometers analysed in this study, the average uncertainty in erythema spectral irradiance ranged between 2.7 % and 3.9 %, with maximum values varying from 17 % for a single Brewer to 3.4 % for a double Brewer. This variability indicates the need of characterising each Brewer spectroradiometer individually rather than relying on generic values, which may not fully exploit the precision these instruments can achieve (Gröbner et al., 2006). The development of well-founded operational procedures, as proposed in this study, is therefore crucial. When integrating erythema spectral irradiance to compute the UV Index (UVI), the resulting uncertainty ranges from 0.28% to 0.53%. The UVI, along with cumulative erythema irradiance doses, represents a fundamental metric for informing the public about the potential adverse effects of UV radiation (Lucas et al., 2019).



The Radiation Amplification Factor (RAF) is used for quantifying the impact of total ozone column (TOC) variations on different biological action spectra. For integrated erythral irradiance, the RAF is approximately 1.35 %, meaning that a 1 % decrease in TOC would lead to a 1.35 % increase in erythral irradiance (Madronich et al., 1998). Given the uncertainty range of spectral irradiance between 2.7 % and 3.9 %, a 1 % change in TOC would not be detectable at the spectral level with a Brewer spectroradiometer. However, for an integrated product like the UVI, where the estimated uncertainty ranges from 0.38 % to 0.53 % for the ten evaluated instruments, a 1 % TOC variation could be detected as a trend in the UV Index. These findings highlight the importance of accurately quantifying the uncertainty in the measurements to determine the minimum detectable variations in different biological effects.

Beyond its scientific interest, a precise quantification of the uncertainty has significant implications for regulatory frameworks. Thus, it facilitates the definition of threshold values and reference doses in risk assessment scales, contributing to the development of more precise regulations on UV exposure limits, particularly for outdoor workers (Vecchia et al., 2007). Furthermore, it enhances confidence in the determination of these indices by enabling more reliable and precise error propagation, ultimately resulting in more robust public health warnings.

In addition, accurate uncertainty characterization plays an essential role in improving UV protection standards for textiles, plastics, and sunscreens, ensuring safer and more effective products for consumers (Young et al., 2017). In particular, it helps defining more detailed and reliable protection thresholds, to improve product comparability so that consumers and professionals can make better-informed decisions, to optimize materials and formulas so that manufacturers can tune the protective properties of their products, and to increase confidence in certification and labelling processes so that they accurately reflect the actual protection offered.

The methodology proposed in this study enables sensitivity analyses to assess the benefits of reducing uncertainty in different error sources. This information is particularly valuable 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 % (Grobner et al., 2023). More advanced developments, such as QASUMEII, have further improved accuracy, with a combined uncertainty of 1.01 % between 310 and 400 nm and 3.67 % at 300 nm (Hülsen et al., 2016).



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Another important application of this study is improving the validation of satellite-based UV radiation products from instruments such as OMI, TROPOMI, and TEMPO. The accuracy of these satellite-derived products, including UV radiation indices and total ozone estimates, is critical for scientific and public health applications (Klotz et al., 2024; Tanskanen et al., 2007). Typically, the relative uncertainty in satellite UV irradiance measurements is expected to be below 5 %, making accurate ground-based uncertainty assessments crucial for validation efforts.

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Finally, uncertainties in UV radiation measurements can significantly impact studies of tropospheric ozone photolysis rates, which vary rapidly with time of day, season, and geographic location. High uncertainty levels in UV measurements may obscure short-term ozone variations, complicating the detection of rapid changes in ozone chemistry, such as morning NO₂ peaks. Reducing measurement uncertainty enhances the resolution of atmospheric models, enabling more accurate simulations of ozone peaks and troughs (Monks et al., 2015).

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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 spectroradiometer measurements.

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6 Conclusions

The uncertainties of the UV spectra measured by eight double and two single monochromator Brewer spectrometers have been estimated using a Monte Carlo method. The UV scans studied were performed during the 18th RBCC-E intercomparison campaign at El Arenosillo (Huelva, Spain).

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Using the information provided by participating operators and EuBrewNet, the uncertainty sources of the ten Brewers were characterised. This was difficult since the available data for many uncertainty sources was either limited (such as radiometric stability, stray light, and noise) or unavailable (cosine error and temperature dependence). Therefore, further work is needed to characterise the Brewer network thoroughly. Furthermore, this study also shows the necessity of establishing coherent QC procedures. The results obtained in this work may vary from the QC performed by other Brewer operators as their instrument characterisation and processing algorithms can be different.

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Once characterised, the combined standard uncertainty (absolute and relative values) was derived and a sensitivity analysis was performed to identify the most influential uncertainty sources.

The absolute combined standard uncertainty of single and double monochromator Brewers depended on the wavelength and SZA, increasing as wavelength rose and SZA declined. For single Brewers, the absolute values tripled those of double Brewers due to stray light. Small differences between double Brewers were observed, due to the influence of (a) dark counts and noise below 300 nm and (b) dead time and cosine correction at larger wavelengths. Regarding the relative values (the

605



absolute combined standard uncertainty divided by the UV irradiance measured) of all Brewers (single and double), it is instrument specific and varies between 2.5 % and 5 % for wavelengths larger than 300 nm. For most of the Brewers studied, the relative uncertainty showed no spectral nor angular dependency. This behaviour is linked to the dominant uncertainty sources. If radiometric stability is the dominant source, the relative combined uncertainty shows no spectral nor SZA dependency, as the stability doesn't have either of these dependencies. On the other hand, if the cosine error of the instrument is significant, then the relative uncertainty will depend on both wavelength and SZA. Furthermore, spikes in the relative combined standard uncertainty are expected if the wavelength shift is large enough. A shift of 0.1 nm can lead to uncertainties of 5 % in the UV-A region.

The sensitivity analysis performed showed that the uncertainty in the Brewer signal (noise, dark counts, stray light, and dead time) is important for wavelengths below 300 nm and large SZAs. However, it can also become significant above 310 nm and for SZAs below 50° if the uncertainties of dead time and SNR are larger than 3 ns and 10 %, respectively. For wavelengths above 300 nm, cosine correction (when implemented), radiometric stability, and the irradiance of the reference lamp were usually the most dominant sources, regardless of the SZA. Radiometric stability was the most influential out of these three uncertainty sources, causing an irradiance uncertainty of 3 %.

Based on the findings of this sensitivity analysis, to reduce the overall uncertainty of a Brewer spectrometer, it is recommended to (a) monitor the instrument' stability by calibrating it more than once a year, (b) replace the traditional entrance optics to improve the angular response, (c) monitor the dead time and wavelength shifts to ensure uncertainties of less than 2 ns and 0.05 nm, respectively, and (d) reduce the errors committed in the calibration of reference lamps.

Finally, it should be noted that further work is needed to ensure that the uncertainty of all UV scans measured by Brewer spectroradiometers is evaluated. The Monte Carlo method used in this study is easy to implement, but it requires a large number of trials to provide reliable results. Considering the number of uncertainty sources in Brewer measurement procedure, this results in a heavy calculation cost. On a standard laptop, it took around 8 hours per UV scan measured to calculate the combined standard uncertainty and the sensitivity analysis (10^6 iterations). Consequently, the MCM can be impractical to evaluate the uncertainty of Brewers long UV records.

Data and code availability. The data used for this study is available at EuBrewNet (<http://eubrewnet.aemet.es/>) and the code used was based on the algorithm available at Zenodo (González et al., 2024a). Aerosol optical depth measured at INTA/El Arenosillo station was used for the cosine correction and can be downloaded from AERONET (Holben et al., 1998).

Author contributions. Conceptualization, C.G., J.M.V., and A.S.; Methodology, C.G. and A.S.; Software, C.G. and A.S.; Validation, C.G., J.M.V., A.R., J.L.S., J.M.S.A., and A.S.; Formal analysis, C.G. and J.L.S.; Investigation, C.G. and J.M.V.; Resources, J.M.V., A.R., J.L.S., J.M.S.A., R.K., A.R.D.S., P.B., A.D., N.J., and G.G.; Data Curation, C.G., J.M.V., A.R., J.L.S., and A.S.; Writing – Original Draft, C.G.; Writing – Review & Editing, J.M.V., A.R., J.L.S., J.M.S.A., R.K., A.R.D.S., P.B., A.D., N.J., G.G., and A.S.; Visualization, C.G.; Supervision, J.M.V., A.R., and A.S.; Funding acquisition, J.M.V.



Competing interests. The authors declare that they have no conflict of interest.

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