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Aerosol optical depth in the European Brewer Network

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Abstract. The high spatial and temporal variability of aerosols make networks capable of measuring their properties in near real time of high scientific interest. In this work we present and discuss results of an aerosol optical depth algorithm to be used in the European Brewer Network, which provides data in near real time of more than 30 spectrophotometers located from Tamanrasset (Algeria) to Kangerlussuaq (Greenland). Using data from the Brewer Intercomparison Campaigns in the years 2013 and 2015, and the period in between, plus comparisons with Cimel sunphotometers and UVPFR instruments, we check the precision, stability, and uncertainty of the Brewer AOD in the ultraviolet range from 300 to 320 nm. Our results show a precision better than 0.01, an uncertainty of less than 0.05, and a stability similar to that of the ozone measurements for well-maintained instruments. We also discuss future improvements to our algorithm with respect to the input data, their processing, and the characterization of the Brewer instruments for the measurement of aerosols.

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1 Introduction

Concerning atmospheric physics and chemistry, it is well known that aerosols play an important role in processes like the interaction with the solar radiation and the formation of clouds, which are key in our understanding of the radiative balance of the Earth-Atmosphere system. As pointed out in the IPCC Fifth Assessment Report (IPCC, 2014), the high spatial and

5 temporal variability of aerosols, and the different absorbing properties depending on their type, add a large uncertainty to the radiative forcing estimations. This makes networks capable of measuring aerosol properties, over a wide spatial range, in near real time, of special importance for the study of climate change. Of course, other research topics, from satellite validation to the assessment of aerosol-related health issues, also benefit from the availability of these datasets.

Previous works have already demonstrated the capability of Brewer spectrophotometers, usually devoted to the measure-

10 ment of the total ozone column (TOC) and UV irradiance, to determine the aerosol optical depth (AOD), see e.g. Harrison and Michalsky (1994); Bais (1997); Marenco et al. (1997); Carvalho and Henriques (2000); Gröbner et al. (2001); Marenco et al. (2002); Cheymol and De Backer (2003); Arola (2004); Gröbner and Meleti (2004); Silva and Kirchhoff (2004); Kazadzis et al. (2005); Savastiouk (2006); Sellitto et al. (2006); Kazadzis et al. (2007); De Bock et al. (2010); Kumharn (2010); Kumharn et al. (2012); De Bock et al. (2014); Kumharn et al. (2015); Rodriguez-Franco (2015); Carlund (2016); Diémoz

15 et al. (2016); Kumharn and Hanprasert (2016). Within the framework of COST Action ES1207, "a European Brewer Network" (EUBREWNET, Rimmer et al. (2017), http://www.eubrewnet.org/cost1207), and as part of the activities carried out at the WMO-CIMO Testbed for Aerosols and Water Vapor Remote Sensing Instruments (Izaña, Spain), we have developed an AOD algorithm to be used by the more than 30 Brewer spectrophotometers integrated in the network. All the necessary data for the AOD determination in the 300 to 320 nm wavelength range can be obtained from the standard ozone, direct sun measurements,

20 which are available in near real time at EUBREWNET's dataserver (http://rbcce.aemet.es/eubrewnet). Besides providing four ozone product levels (three in near real time) with increasing accuracy, this dataserver also allows for the harmonization and automatic quality control of the Brewer data.

Also needed for the determination of the AOD is the data provided by the instrumental calibration performed by the Regional Brewer Calibration Center for Europe (RBCC-E) during the annual intercomparison campaigns. To carry out this task,

25 the RBCC-E maintains a reference triad of Brewer spectrophotometers at the Izaña Atmospheric Observatory (IZO, Agencial Estatal de Meteorología, Spain), located at 2370 m.a.s.l. in the island of Tenerife. Most of the year, the meteorological conditions at IZO are excellent for the absolute calibration of the Brewer instruments via the well-known Langley calibration method (Ångström, 1970; Shaw et al., 1973). Further helping to the calibration process are the multiple research programs carried out at IZO, which provide all the necessary support information (for an overview of the recent activities carried out at

30 the observatory, see Cuevas et al., 2015). This absolute calibration is transferred every year at an international intercomparison campaign, carried out in alternate years at El Arenosillo Atmospheric Observatory (Instituto Nacional de Técnica Aeroespacial, Huelva, Spain) and the Arosa Lichtklimatisches Observatorium (MeteoSwiss, Switzerland). For an overview of the last three campaigns, see Redondas et al. (2015); Redondas and Rodriguez-Franco (2015a, b).

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The present work is organized as follows. Our AOD algorithm is described in Sect. 2. In Sect. 3 we first give details of the calibration of selected Brewers carried out in 2013, and derive the precision of these instruments for the AOD determination. Next, we check the stability of the AOD in these Brewer instruments in the approximately two-year period between the Eighth and Tenth Intercomparison Campaigns of the RBCC-E, both held at El Arenosillo. For this, we compare the Brewer AOD

5 with data of collocated Cimel sun-photometers as provided by the Aerosol Robotic Network (AERONET). Next, using data acquired during the Tenth Intercomparison Campaign of the RBCC-E, we compare the Brewer AOD with the data produced by an Ultraviolet Precision Filter Radiometer (UVPFR) and derive the Brewer AOD uncertainty. Finally, in Sect. 4 we discuss future improvements of our AOD algorithm, and in Sect. 5 we provide some closing remarks.

2 Method

10 We begin this section providing a short overview of the Brewer spectrophotometer. Next, we describe the Brewer AOD equation used in our algorithm, placing special emphasis on the origin of each term. This is followed first by a description of the calibration procedure, and then by an analytic derivation of the AOD uncertainty within some simplifications. Finally, we briefly describe the Cimel and UVPFR instruments used in this work to compare with the Brewer spectrophotometer.

2.1 The Brewer spectrophotometer

15 The Brewer spectrophotometer was developed in Canada during the 1970s, and a commercial, automated version became available in the early 1980s. Nowadays, it is one of the primary ground-based instruments used to report TOC data, together with the Dobson spectrometer. The Brewer spectrophotometer makes measurements of the direct spectral UV irradiances and, through a well-defined process, produces a TOC value. A complete description of the instrument and the measurement process can be found in Kerr (2010), but we highlight next the most relevant details for the present work.

20 The Brewer spectrophotometer detects the direct spectral irradiance in six channels in the UV (303.2, 306.3, 310.1, 313.5, 316.8, and 320.14 nm), each with approximately a 0.5 nm bandwidth (resolving power $\lambda/\Delta\lambda \approx 600$), although that of the shortest wavelength varies with the Brewer model. The spectral analysis is achieved by a holographic grating in combination with a slit mask which selects the channel to be analyzed by a photomultiplier. There are three types of Brewer instruments: the Mk II and Mk IV models are single monochormators, and the Mk III model is a double monochromator, a characteristic

25 that reduces the effect of stray light on its measurements (Karppinen et al., 2015).

During direct sun measurements, sunlight enters the instrument through an inclined quartz window. A right-angle prism directs the incoming light from the Sun to the optical axis of the instrument. The light subsequently passes through the fore-optics, made up by a set of lenses to adequately focus the beam, an iris diaphragm, and two filter wheels, which are used to adjust the light intensity entering the system. A ground quartz diffuser is located on the first filter wheel. The second filter

30 wheel consists of a set of five neutral density filter attenuators and guarantees that the detector is working in its linear regime. After passing by the filter wheels, radiation is then focused onto the entrance slit of the spectrometer.

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The Brewer retrieval of the TOC requires some instrument characteristics which are determined by calibration experiments during intercomparison campaigns (see e.g. the GAW reports of the Seventh, Eighth, and Ninth Intercomparison Campaigns of the RBCC-E, Redondas et al., 2015; Redondas and Rodriguez-Franco, 2015a, b). The instrumental calibration includes all the parameters that affect the counts measured by the spectrometer, in particular the dead time correction, temperature

5 coefficients, and filter attenuations. The wavelength calibration determines the ozone and Rayleigh absorption coefficient. The exact wavelengths measured by each Brewer spectrophotometer are slightly different from instrument to instrument. The so-called "dispersion test" is thus used to determine the exact wavelengths of each instrument and its slit, or instrumental, function. An extraterrestrial (calibration) constant is determined by the Langley method or by comparison with a reference instrument. The TOC is then finally determined using ratios of measurements at four wavelengths. In contrast, the individual (absolute)

10 measurements are used for the determination of the AOD together with calibration parameters specific for each wavelength, as discussed next.

2.2 AOD equation for Brewer spectrophotometers

The attenuation of the direct solar irradiance as it travels through the Earth's atmosphere is described by the well known Beer-Lambert-Bouguer equation (see e.g. Iqbal, 1983):

15 $$I = I_0 e^{-\boldsymbol{\tau} \boldsymbol{m}} \tag{1}$$

where I is the direct solar irradiance measured at the ground, I_0 is the extraterrestrial (outside the atmosphere) solar irradiance, $\boldsymbol{\tau}$ is the so-called optical depth, and $\boldsymbol{m}$ is the optical air mass. Note that, instead of absolute irradiances, proportional magnitudes can be used, like for example measured photon rates. The two parameters $\boldsymbol{\tau}$ and $\boldsymbol{m}$ describe the attenuation of the solar radiation by the different components of the atmosphere. In the UV range and for cloudless conditions, the main

20 contributions are produced by the ozone, nitrogen and sulfur dioxides, Rayleigh molecular scattering, and aerosols. Following previous authors (e.g., Marenco et al., 2002) we currently do not consider the contribution of the nitrogen and sulfide dioxides to the optical depth, which should be rather small in the UV range except at polluted sites (Carlund et al., 2017). Under these assumptions, the optical depth can thus be written as

$$\boldsymbol{\tau m} = \tau_o m_o + \tau_R m_R + \tau_a m_a \tag{2}$$

25 where the subscripts refer to the contributions by ozone (o), Rayleigh (R), and aerosols (a).

Solving for the aerosol optical depth τ_a, Eq. 1 then becomes

$$\tau_a = \frac{1}{m_a} \left\{ \log_e I_0 - \log_e I - \tau_o m_o - \tau_R m_R \right\} \tag{3}$$

Note that Eq. 3 is wavelength dependent and, in particular, is valid for each wavelength λ measured by the Brewer spectrophotometer. In this work we will consider only the five wavelengths between 306.3 and 320.1 nm which are measured by all

30 Brewer models. The wavelength at 303.2 nm has a variable bandwith which depends on the Brewer model, and others above 320.1 nm are only routinely measured by Mk IV models.

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In terms of variables either measured by the Brewer spectrophotometer or determined by the calibration carried out by the RBCC-E, Eq. 3 can be rewritten as (see Appendix A for the corresponding expression written in the scaled logarithmic space used internally by the standard Brewer software)

$$\tau_a(\lambda) = \frac{1}{m_a} \{ \log_e I_0(\lambda) - \log_e I(\lambda) - X_o k_o(\lambda) m_o - \frac{p}{1013} \tau_{R0}(\lambda) m_R \} \quad (4)$$

5   where the variables are

- $I_0(\lambda)$: extraterrestrial counts per second for each wavelength, determined by any of the two calibration methods described in Sect. 2.3.

- $I(\lambda)$: counts per second measured by the Brewer instrument at each wavelength. Besides the usual corrections applied to the raw counts in the standard ozone data reduction (Kipp and Zonen, 2014), we also apply the ones described below.
10   This requires the determination of some parameters which are specific of each Brewer instrument, a process which is carried out during the instrumental calibration performed by the RBCC-E.

- X_o: measured TOC in atm-cm. We currently use the real-time ozone level 1.5 product available at EUBREWNET's data server, with the Rayleigh contribution calculated using spectral coefficients specific for each Brewer, as determined during the RBCC-E calibration. This modification in the Rayleigh contribution with respect to the coefficients supplied
15   by default with the Brewer instruments lowers the ozone value in approx. 0.003 cm, in agreement with the value reported by Kiedron and Stierle (2009).

- $k_o(\lambda)$: ozone absorption coefficients derived from the Bass and Paur cross sections for each wavelength in cm^{-1}. These coefficients are also determined during the standard ozone calibration performed by the RBCC-E for each Brewer spectrophotometer (see Redondas et al., 2014, for further details).

20   - m_o: ozone optical air mass, calculated as

$$m_o = 1/\cos\{\arcsin[k\sin(sza)]\} \quad (5)$$

where $k = 6370/(6370 + h)$, $h = 22\text{km}$, and sza is the solar zenith angle in degrees.

- p: climatological pressure at the observation site, in millibars.

- τ_{R0}: Rayleigh optical depth at sea level following the prescription of Nicolet (1984), for each wavelength determined
25   during the RBCC-E calibration process.

- m_R: Rayleigh optical air mass, calculated with the same expression as the ozone optical mass but for an altitude $h = 5\text{km}$.

- m_a: aerosol optical air mass, which we approximate by m_R.

As mentioned above, starting from the raw counts measured by the Brewer instrument, the counts per second used in the AOD calculation are determined taking into account the effects produced by the dark counts, dead time, and temperature in the same way as in the ozone data processing (Kipp and Zonen, 2014). Further AOD-specific corrections include

5

– Filter correction, to remove the effect of the different attenuation of each one of the filters used by the Brewer instrument to avoid the saturation of the photomultiplier. This correction is also applied in the ozone data reduction, but here we include the wavelength dependence of the attenuation coefficients, as determined during the calibration process. Note however that we perform our Langley calibration with all the filters by separate (see Sect. 2.3 next), so that any remaining effect of the different attenuations is taken into account in the calibration constants.

10

– Internal polarization correction, to correct for the loss of sensitivity of the Brewer due to the polarization effects produced by its window and grating, mostly noticeable when operating at high solar zenith angles. We use the correction from the field experiment performed by Cede et al. (2006)

– Correction for the seasonal variation of the Earth-Sun distance, using the eccentricity correction factor of the Earth's orbit from Spencer (1971), as quoted by Iqbal (1983):

15
$$E_0 = 1.000110 + 0.034221\cos(\Gamma) + 0.001280\sin(\Gamma)$$
$$+ 0.000719\cos(2\Gamma) + 0.000077\sin(2\Gamma) \quad (6)$$

where $\Gamma = 2\pi(\text{day number} - 1)/365$

To these corrected counts per second we also apply the data-quality filters defined within EUBREWNET's level 1.5 ozone product (see http://rbcce.aemet.es/dokuwiki/doku.php for further details):

20

– Standard deviation (or cloud) filter, used to remove groups of five measurements with large variability (standard deviation above 2.5 DU) and thus likely affected by fast-moving clouds.

– Optical air mass filter, used to remove measurements taken under conditions of high ozone optical air mass (above 3.5), unreliable due to the fast rising and setting of the Sun in low and mid latitudes, and affected by stray light errors in Mk II and IV instruments (Karppinen et al., 2015).

25

– Mercury lamp filter, to remove measurements likely affected by a wavelength shift usually produced by temperature changes in the grating of the Brewer spectrophotometer.

Furthermore, following Gröbner and Meleti (2004), we also remove groups of five AOD measurements for which their standard deviation is greater than 0.02.

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2.3 AOD calibration of Brewer instruments

In this section we provide details of two AOD calibration methods for Brewer spectrophotometers. The Langley plot method is used to calibrate our reference Brewer spectrophotometer operating at IZO. The calibration transfer method is then used to calibrate other Brewer instruments operating simultaneously with our Brewer reference during the intercomparison campaigns.

5   Under the stable atmospheric conditions in which Brewer calibrations take place, the total optical depth τ can be considered constant. Equation 1 can then be rewritten as a linear equation with the total optical air mass m as the independent variable and $\log_e I_0$ as the intercept:

$$\log_e I = -\boldsymbol{\tau}\boldsymbol{m} + \log_e I_0 \tag{7}$$

Following the Langley plot method, the determination of the calibration constant I_0 then just requires fitting a linear equation
10   to the data of a $\log_e I$ *vs.* m plot. Note that this equation is valid for each wavelength and filter position, multiple Langley fits being thus necessary to determine all the calibration constants. We show an example in Sect. 3.1.

In practice, we follow Gröbner and Kerr (2001), and apply the Langley plot method using

$$\log_e I + \frac{p}{1013}\tau_{R0}m_R = -\tau'm_o + \log_e I_0 \tag{8}$$

where the Rayleigh term is considered explicitly, so that the τ' optical depth now contains the contributions from the ozone and
15   aerosols, as it also happens with the optical air mass. However, during a large part of the year the atmospheric conditions at IZO can be considered ideal for the Langley calibration method, in particular usually featuring a low aerosol load except in summer months (see e.g. Rodríguez et al., 2015; García et al., 2017). In these conditions, the largest contribution to τ' in the UV range is produced by ozone, and m_o can indeed be considered a good approximation for the optical air mass on the right hand side of Eq. 8. A more elaborate term for the optical air mass could be used instead, like e.g. the average weighted by the optical depths
20   proposed in Carlund et al. (2017). However, we have found that in the atmospheric conditions of IZO and within the optical air mass limits described below, switching from m_o to m_a produces differences of $\sim 0.01\%$ in the calibration constants obtained from the Langley plot, so we don't expected any combination of the two air masses to introduce any significant changes.

Following the usual ozone calibration procedure for Brewer spectrophotometers (see e.g., Redondas, 2008), we make separate Langley plots for each half day if there are at least 20 observations taken with the same filter, and consider optical air
25   masses between 1.1 and 3.5. Finally, we average the calibration constants obtained over a period of 1-2 months, discarding those corresponding to linear regressions with r^2 coefficients of determination below 0.995, and/or above/below 1.20 times the median.

Performing this Langley calibration procedure at IZO, we usually obtain calibration constants for just two filters (#2 and #3), leaving another 4 filter positions without characterization. This includes filter positions #0 and #1, which are frequently
30   used at high-latitude sites because they correspond to lower attenuations (actually, in position #0 no filter is used). To get a more complete calibration for our reference instrument, another Langley calibration is performed, but with less demanding limits – an extended optical airmass range from 1.1 to 5.5, and a lower tolerance of 0.9 for the r^2 coefficient of the linear regression. This less-demanding calibration usually produces results for filters #0 to #3, but at the price of a higher uncertainty.

In order to retain the lower uncertainty of the more-demanding calibration, from the results of the less-demanding Langley we only use the differences between calibration constants of different filters. When added to the results for filter positions #2 and #3 of the more-demanding calibration, these differences allow us to determine calibration constants for filter positions #0 and #1. This is thus the calibration of the reference Brewer spectrophotometer that we transfer to other Brewer instruments during

5   intercomparison campaigns.

If the Brewer spectrophotometer to be calibrated is operating at the same place and simultaneously with a reference instrument already producing correct AOD values, Eq. 4 can be solved for the calibration constant:

$$\log_e I_0 = \tau_a^{\text{ref}} m_R + \log_e I + X_o k_o m_o + \frac{p}{1013} \tau_{R0} m_R \tag{9}$$

Here, the τ_a^{ref} AOD value is provided by the reference instrument, and the remaining data are measured by the Brewer being

10 calibrated. Eq. 9 is valid for each simultaneous measurement, with a specific wavelength and filter position. The complete set of calibration constants I_0 can thus be determined solving this equation for multiple measurements taken under different conditions.

The last days of the intercomparison campaigns of the RBCC-E, after the Brewer instruments have received maintenance and their ozone calibrations have been updated or confirmed, provide the necessary time span to carry out this calibration

15 transfer procedure. Measurements within 1 minute of the reference instrument are considered simultaneous, and the average of multiple calibration constants for each wavelength and filter position provides the final AOD calibration constants.

In Sect. 3 we will show results for selected Brewer spectrophotometers which took part in both the Eighth and Tenth Intercomparison Campaigns of the RBCC-E, held in the years 2013 and 2015, respectively, at El Arenosillo Atmospheric Observatory. Brewer #185, the travelling standard of the IZO triad, was present at both campaigns, and has been used as

20 reference to calibrate other participating instruments by the calibration transfer method just described. The travelling standard of the RBCC-E itself was calibrated using the Langley plot method, following the procedure described at the beginning of this section.

2.4   Brewer AOD uncertainty

A full analytic derivation of the uncertainty is outside the scope of this paper. However, we will consider here a simplified

25 model, taking into account only the three largest contributions found by Carlund et al. (2017) to the total uncertainty in the UV range for the UVPFR instrument, whose AOD algorithm shares similarities with that of the Brewer. We also assume no correlation between variables, and work within the approximation $m_a \approx m_o \approx m_R$. In these conditions, we write the AOD uncertainty as

$$u(\tau_a) = \sqrt{u^2(\tau_o) + \frac{u^2(I_0)}{I_0^2} + \frac{u^2(p)\tau_{R0}^2}{1013^2}} \tag{10}$$

30 where each uncertainty u on the right hand side includes, if necessary, a factor 2 to translate from 1σ to 2σ level (GUM, 2008), and arise from

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- the ozone optical depth, which has been found by Carlund et al. (2017) to be the largest contribution in the UV range for the UVPFR instrument. Ignoring the correlation between variables, the uncertainty of the ozone optical depth can be approximated by $u^2(\tau_o) = u^2(X_o)k_o^2 + X_o^2 u^2(k_o)$

- calibration, which is the second largest contribution according to Carlund et al. (2017), and which contributes $u^2(I_0)/I_0^2$
5   to the total uncertainty,

- pressure, which we keep fixed at a climatological value for each station, thus introducing a term $u^2(p)\tau_{R0}^2/1013^2$

For the uncertainty of the ozone optical depth, we can assume an average ozone of 340 Dobson units with 1% uncertainty, values which correspond to Brewer #185 during the Tenth Intercomparison Campaign of the RBCC-E at El Arenosillo. Ozone absorption coefficients for the wavelengths between 310 and 320 nm of Brewer #185 range from 2.31 to 0.67 cm^{-1}, with a
10 2.1% uncertainty according to Weber et al. (2016). This results in a 2σ uncertainty of the ozone optical depth between 0.04 and 0.01. The uncertainty associated with the calibration can be approximated by the relative standard deviation of the series of calibration constants calculated in the Langley calibration. In our case, this value is 1% at the most for all wavelengths and filters. For the pressure term, the Rayleigh coefficients of Brewer #185 at sea level are ~ 1 at all wavelengths, and we will consider a 1σ uncertainty of 5 hPa.

15 Within all the approximations considered in this simplified model, the standard AOD uncertainty at the 95% level is then 0.04–0.02 in the 310–320 nm wavelength range. An analogue calculation produces 0.06 for the standard uncertainty at 306.3 nm. As we will see in Sect. 3.3, there is a fair agreement between these values and those determined in the Brewer-UVPFR comparison. Regarding previous works, Kazadzis et al. (2005) has reported a 2σ uncertainty of ~ 0.1 for the Brewer AOD in the UVA range, and Carlund et al. (2017) has recently calculated an uncertainty better than 0.02 for the UVPFR
20 instrument operating close to 320 nm.

2.5 Cimel and UVPFR instruments

During the period considered in this work, the Cimel sunphotometer model CE318-N was the standard instrument of AERONET. The sunphotometer performs automatic direct-sun measurements every 15 minutes at 340, 380, 440, 500, 675, 870, 940, 1020 and 1640 nm nominal wavelengths with a 1.2 ° field of view. The value of the full width at half maximum (FWHM) is 2 nm. So-
25 lar extinction measurements are used to derive spectral AOD and the corresponding Ångström exponent (Holben et al., 1998). The estimated AOD uncertainty is approximately 0.01, increasing up to 0.02 in the UV wavelengths (Eck et al., 1999; Holben et al., 2001). Data acquisition protocols, calibration procedures and data processing methods have been extensively described, see e.g. Holben et al. (1998); Dubovik et al. (2000); Smirnov et al. (2000). We use the highest quality data currently available for Cimel sunphotometers, the cloud-screened and quality-assured version 2 level 2.0 product downloaded from the AERONET
30 site (http://aeronet.gsfc.nasa.gov). We use the shortest wavelength provided, 340 nm, and the 340–440 Ångström exponent to extrapolate to 320 nm, this being the longest wavelength measured by the Brewer in its most usual ozone operational mode.

The UVPFR sunphotometer is a special version of the Precision Filter Radiometer (PFR) designed and built at the Physikalisch-Meteorologisches Observatorium Davos and World Radiation Center (PMOD/WRC) in Davos, Switzerland. It measures the
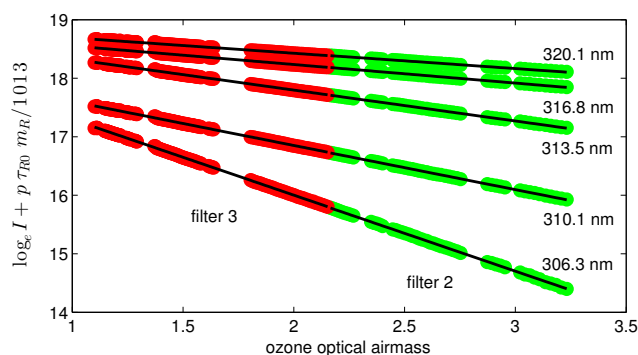
Figure 1. Langley plots for the five Brewer wavelengths between 306.3 nm and 320.1 nm, for measurements taken with filters 2 (green) and 3 (red) of Brewer #185 operating at IZO in the morning of May 31st 2013.

direct solar irradiance at the four nominal wavelengths 305, 311, 318 and 332 nm. The filters and detectors are operated at a constant temperature of 20°C and are exposed to solar radiation only during actual measurements. In order to perform direct sun measurements, the UVPFR is mounted on a sun-tracker so that it is continuously pointing to the Sun. Direct sun measurements are taken each full minute and the stored signal values are averages of 10 samples for each channel made over a total duration of 1.25 seconds. The width of the spectral response functions is in the order of 1.0-1.3 nm at FWHM. Both Langley calibrations and AOD retrievals are affected by the finite FWHMs. Corrections to reduce this influence, together with more detailed information about the UVPFR, are described by Carlund et al. (2017). Where necessary for our comparisons, the UVPFR data at the closest wavelengths to those of the Brewer have been interpolated using the Ångström relation.

3 Results

In this section we use data from the Eighth and Tenth Intercomparison Campaigns of the RBCC-E, and the period in-between, to analyze

1. the precision of the Brewer AOD data, by checking Brewer-Brewer comparisons (Sect. 3.1);

2. the stability of the Brewer as an AOD-measurement instrument over a 2 year period, by comparing Brewer and Cimel data (Sect. 3.2); and

3. the uncertainty of the Brewer AOD data, by comparing with Cimel and UVPFR instruments (Sect. 3.2 and 3.3).

3.1 Precision and Brewer-Brewer comparison

In this Section we discuss the calibration of different Brewer spectrophotometers in the year 2013, starting with Brewers #183 and #185, both belonging to the RBCC-E triad based at IZO. These instruments were independently calibrated at IZO via the Langley procedure described in Sect. 2.3, using data from April 1st to June 3rd for Brewer #183, and from May 7th to June

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Table 1. Summary of the AOD comparison between Brewer #185 and selected instruments – Brewers #183, #070, #075, #186, #201, and #202, the first also calibrated by the Langley-plot method, and the last five by transfer from Brewer #185. We show the ID and model of each instrument, the total number of simultaneous observations within 1 minute with Brewer #185, and, for each nominal Brewer wavelength, the Pearson's correlation coefficient between the two AOD datasets and the median and standard deviation of their differences.

Brewer		correlation, median of differences, standard deviation of differences				
(Mk)	obs.	306.3 nm	310.1 nm	313.5 nm	316.8 nm	320.1 nm
calibrated by the Langley method						
183 (III)	4695	0.934, 0.0002, 0.0105	0.967, 0.0031, 0.0073	0.975, 0.0033, 0.0064	0.981, 0.0047, 0.0055	0.985, 0.0039, 0.0050
calibrated by transfer from Brewer #185						
070 (IV)	438	0.783, -0.0003, 0.0365	0.948, 0.0000, 0.0145	0.955, 0.0000, 0.0136	0.955, -0.0001, 0.0133	0.955, -0.0001, 0.0133
075 (IV)	303	0.863, -0.0007, 0.0288	0.972, -0.0002, 0.0133	0.972, 0.0000, 0.0134	0.978, -0.0001, 0.0115	0.976, 0.0000, 0.0119
186 (III)	509	0.931, 0.0001, 0.0127	0.960, 0.0001, 0.0092	0.967, 0.0001, 0.0083	0.971, 0.0001, 0.0078	0.973, 0.0000, 0.0075
201 (III)	407	0.907, 0.0001, 0.0106	0.946, 0.0003, 0.0074	0.949, 0.0002, 0.0069	0.956, 0.0001, 0.0064	0.955, 0.0001, 0.0063
202 (III)	464	0.983, 0.0002, 0.0090	0.992, 0.0000, 0.0062	0.993, 0.0001, 0.0057	0.994, 0.0001, 0.0054	0.994, 0.0000, 0.0053
Median	438	0.907, 0.0001, 0.0127	0.960, 0.0000, 0.0092	0.967, 0.0001, 0.0083	0.971, 0.0001, 0.0078	0.973, 0.0000, 0.0075

3rd in the case of Brewer #185. Both instruments were shipped to the Eighth Intercomparison Campaign of the RBCC-E, held in El Arenosillo (Huelva) in June 2013, and this sets the end of these date ranges. Regarding the starting dates, atmospheric conditions at IZO were not appropriate for the Langley calibration before the beginning of April, and furthermore Brewer #185 experienced instrumental issues in this month, leaving us with roughly two months of data for the Langley calibration of

5 Brewer #183 and one month for Brewer #185. As an example, Fig. 1 shows the Langley plots for the five wavelengths measured by Brewer #185 in one morning. Because we have considered data for each filter by separate, we obtain calibration constants for each wavelength and filter. The difference between filters is $\sim 1\%$ at most, showing that the filter correction applied to the data (see Sect. 2.2) mostly removes their differences in attenuation.

For the four longest wavelengths, the comparison between the independently-calibrated Brewers #183 and #185 in Table 1

10 shows correlation coefficients higher than 0.97, and biases (provided by the median of the Brewer-Brewer AOD differences) and standard deviations lower than 0.005 and 0.007, respectively. For the lowest wavelength at 306.3 nm, the results are slightly worse, with a correlation of 0.94 and a standard deviation of 0.01. The deterioration of the results at the 306.3 nm wavelength can be explained due to the reduction of the signal to noise ratio as the wavelength becomes shorter, and is a trend we will observe in all the results presented in this work. Still the biases are rather small at all wavelengths, and both Brewers are of the

15 same model and operate under the same conditions, so the standard deviations can be taken as the precision (or instrumental repeatability) at the 1σ level, which ranges from 0.01 at 306.3 nm to 0.005 at 320 nm. For comparison, Carlund et al. (2017)
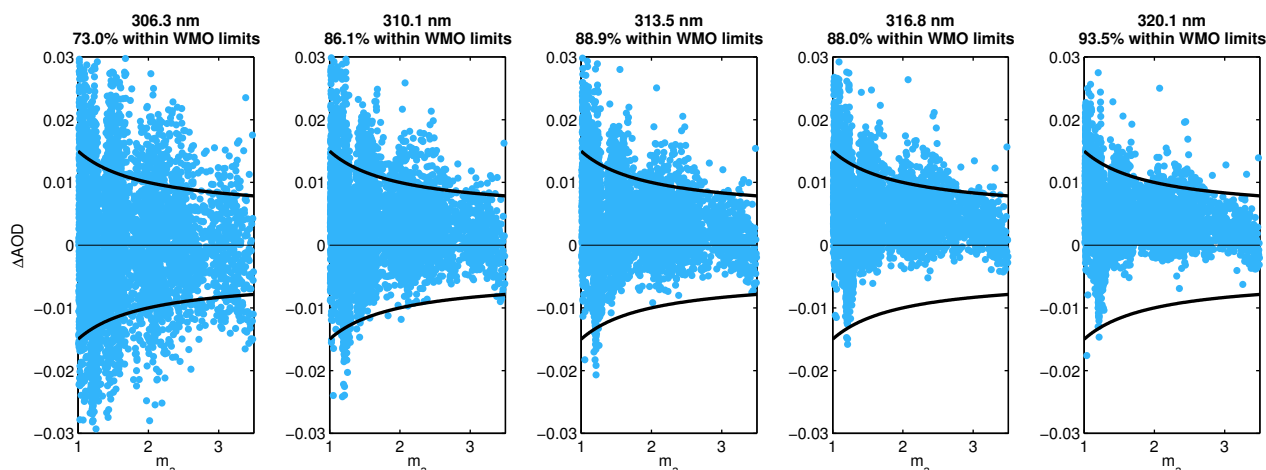
Figure 2. AOD differences between observations within 1 minute of the independently-calibrated Brewers #183 and #185, plotted as a function of the aerosol optical airmass. The WMO traceability limits for finite field of view instruments (Eq. 11) are shown as thick black lines.

have recently reported a precision of 0.01 (1σ) for both UVPFR and Brewer instruments while measuring AOD in the UV. For Cimel instruments measuring total optical depth, Mitchell and Forgan (2003) provides a 1σ precision of better than 0.0025. Note that this latter result corresponds to the visible range and the value corresponding to the UV range will likely be larger, as is also the case with the uncertainty of the Cimel instruments, which increases from 0.01 in the visible to 0.02 in the UV range (Eck et al., 1999).

The WMO traceability criteria (WMO/GAW, 2005) can also be used to check the quality of the AOD measured by the Brewer instruments. For finite field-of-view instruments, this criteria requires at least 95% of the differences between the measurements of two instruments to be within the limits

$$\pm(0.005 + 0.010/m_a) \tag{11}$$

Figure 2 shows the differences in AOD of Brewers #183 and #185 as a function of the aerosol optical airmass (which we approximate by the Rayleigh optical airmass, see Sect. 2.2) together with the WMO traceability limits. The percentages of differences within the limits range from 73% at the shortest wavelength to 93% at the longest. It has to be noted that the WMO traceability criteria requiring 95% of the compared data within the limits of Eq. 11 was originally defined for selected wavelengths where the absorption of trace gases is minimum. In this case, UVB AOD differences of 73% to 93% fulfilling this criterion can be considered quite good. These values are also in the same range as those reported in previous studies involving Brewer instruments. Kouremeti et al. (2014) found percentages between 46 and 88% when comparing independently-calibrated Brewer and Cimel instruments at wavelengths between 306 and 320 nm (extrapolated from 340 nm in the case of the Cimel). Diémoz et al. (2016) calibrated a Mk IV Brewer with respect to a Cimel instrument at 437 nm, finding that 90% of the observations were within the WMO traceability limit once a temperature correction for the Brewer was included. Carlund

et al. (2017) have reported percentages between 85.6% and 97% between UVPFR and Brewer photometers operating in the 306–320 nm range, the Brewer being calibrated using as reference the UVPFR's AOD.

Using the data of the Eighth Intercomparison Campaign of the RBCC-E, held at El Arenosillo (Huelva, Spain) in June 2013, we have been able to transfer the Langley calibration of Brewer #185 to five other instruments, namely Brewers #070 and #186 from Madrid (Spain), #075 from Reading (United Kingdom), and #201 from Tamanrasset (Algeria). Furthermore, we also transferred the same calibration to Brewer #202 from Kangerlussuaq (Greenland), which was present at IZO in November 2013. According to the results in Table 1, Brewers #186, #201, and #202 show results similar to Brewer #183, and thus confirm the precision of 0.01–0.005 for the AOD measurement. Instruments #070 and #075 are however in noticeably worse agreement with the reference. These two Brewer instruments are Mk IV models, while the others (including #183 and #185) are Mk III ones. Very recently, Carreño et al. (2016) have reported that the polarization correction proposed by Cede et al. (2006) might not be adequate for all Brewer models, and these results might point in this direction. Another source of error may be the lack of a correction for the stray light of the single-grating Mk II and IV Brewer spectrophotometers, although in previous studies this has been found to be a non issue for the AOD determination (Silva and Kirchhoff, 2004).

3.2 Stability and Brewer-Cimel comparison

In this section we analyze the stability of the Brewer AOD by comparing with Cimel data over ~ 2 years, from June 2013 to May 2015. We analyze the AOD from Brewer spectrophotometers considered in the previous section, operating at their observation sites. In all cases we compare the Brewer instruments with collocated Cimel sunphotometers, except for the Brewer at Reading for which the closest Cimel is located ~ 60 km away at Chilbolton (Kumharn, 2010).

Figure 3 summarizes the comparison between the Brewer and Cimel AOD in the 2013–2015 period. As shown by the AOD series, there is clear correlation between the data of both instruments, with correlation coefficients above 0.90, the lowest value corresponding to the Reading/Chilboton data, which also shows the largest spread of Brewer-Cimel differences. Besides this instrument, Brewers #070 and #201 show the largest changes. The latter operates at Tamanrasset under extreme aerosol conditions with very frequent dust aerosol intrusions, which makes maintenance of the utmost importance (see e.g., Guirado et al., 2014). Note also that some maintenance issues that do not produce noticeable errors for the determination of TOC might affect the AOD, because the former uses ratios of measurements at different wavelengths while the latter uses their absolute values. Regarding Brewer #070, it should be remembered that in Sect. 3.1 it was found to be one of the instruments in worse agreement with the reference after the calibration transfer. The better behaviour of the collocated Brewer #186 in this 2-years comparison points to a bad calibration and/or to maintenance issues as a possible reason for the instability of Brewer #070 AOD data. Of the remaining instruments, Brewers #183, #185, and #186 remain within the initial Brewer-Cimel AOD difference for a period of at least ~ 1.5 years, from June 2013 to November 2014. The rather good stability of these instruments proves that it is possible to provide quality AOD data when the instrument maintenance is properly performed. It should be noted that Brewer intercomparison campaigns are held every 2 years, fairly close to the 1.5 years stability period mentioned, and would provide an opportunity to check, provide maintenance, and recalibrate the instruments for AOD operation if necessary.

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Although we expect the extrapolated Cimel data to provide a good and stable reference to compare with the Brewer AOD, the uncertainties introduced by the extrapolation, as well as the change of Brewer AOD calibration over the 2 year period, preclude any precise determination of the Brewer uncertainty from the data presented in this section. Still, assuming as in Mitchell and Forgan (2003) that the biases are a systematic error which can be corrected (by using e.g. a different prescription

5 of the ozone absorption coefficients or a different pressure value), the standard deviation of the Brewer-Cimel difference for the three most stable instruments in Fig. 3 results in a standard uncertainty at the 95% (2σ) level (see e.g. GUM, 2008) of $\sim$0.05. From this value and accepting the 2σ uncertainty of 0.02 for the Cimel in the UV mentioned in Sect. 2.5, the uncertainty of the Brewer would be almost 0.05 at 320 nm. In the next section we compare our Brewer AOD with that of an UVPFR instrument.

3.3 Uncertainty and Brewer-UVPFR comparison

10 A better experimental determination of the uncertainty can be derived from the comparison with the UVPFR sunphotometer, independently calibrated and operated by the PMOD/WRC at the Tenth Intercomparison Campaign of the RBCC-E, held at El Arenosillo in May-June 2015. We present results for sixteen of the Brewer instruments present, including reference Brewer #185 from the IZO triad. As in the case of the Eighth Intercomparison Campaign, Brewer #185 was calibrated by the Langley plot method at IZO before the campaign, and this calibration was then transferred to the other Brewer spectrophotometers

15 using simultaneous data acquired after the instruments had received maintenance at the campaign.

The plots of the Brewer-UVPFR AOD differences *vs.* the aerosol optical air mass in Fig. 4 show that some Brewer instruments, like #044 and #172, largely deviate from the expected $1/m_a$ behaviour of the differences (see e.g. Mitchell and Forgan, 2003), while others like e.g. #075 and #117 show a large spread of the data. Both issues might be either related to problems not solved by the maintenance performed during the campaign or to effects not fully considered in our AOD determination

20 method, like e.g. the different polarization corrections required by the different Brewer models. It should also be noted that our method currently only includes one data-quality filter specific for AOD, and this may be insufficient to remove all outliers. Overall, though, Fig. 4 shows a reasonably good agreement between the Brewer and UVPFR instruments, with percentages of differences within the WMO traceability limits similar to those presented in Sect. 3.1. AOD differences with respect to reference Brewer #185 are fairly similar to those shown in Fig. 4, although in the comparison with the UVPFR the differences

25 seem to increase with the optical airmass, something that does not happen in the Brewer-Brewer comparisons.

Table 2 summarizes the comparison between the Brewer and UVPFR data within 1 minute at the five standard Brewer ozone wavelengths. As before, the shortest wavelength shows slightly worse results than the other four. At 306.3 nm, correlation coefficients are above 0.96, and biases and standard deviations below 0.015 and 0.024, respectively. In the range of 310.1 to 320.1 nm, correlations are above 0.97, and biases and standard deviations are lower than 0.009 and 0.020, respectively.

30 The uncertainty of the Brewer AOD can be obtained from the standard deviations in Table 2 and the uncertainty of the UVPFR. Care must be taken, however, to include the effect of terms common to the Brewer and UVPFR AOD. Among these, the largest according to Carlund et al. (2017) is the ozone optical depth τ_o. Taking into consideration only this term, the 2σ

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Table 2. Comparison between the AOD data of the Brewer and UVPFR instruments at the Tenth Intercomparison Campaign of the RBCC-E. We use data from observations within 1 minute and show the same statistics as in Table 1.

Brewer		correlation, median of differences, standard deviation of differences				
(Mk)	obs.	306.3 nm	310.1 nm	313.5 nm	316.8 nm	320.1 nm
005 (II)	618	0.974, 0.0106, 0.0191	0.989, -0.0005, 0.0154	0.989, 0.0029, 0.0115	0.990, -0.0017, 0.0107	0.993, 0.0005, 0.0088
044 (II)	293	0.966, 0.0114, 0.0240	0.977, -0.0001, 0.0196	0.977, 0.0039, 0.0175	0.980, -0.0010, 0.0154	0.982, 0.0010, 0.0141
070 (IV)	165	0.974, 0.0091, 0.0092	0.989, -0.0035, 0.0064	0.989,-0.0001, 0.0059	0.990, -0.0055, 0.0056	0.991, -0.0021, 0.0052
075 (IV)	1081	0.969, 0.0052, 0.0225	0.975, -0.0073, 0.0200	0.975,-0.0052, 0.0195	0.976, -0.0092, 0.0188	0.977, -0.0069, 0.0181
117 (IV)	810	0.972, 0.0072, 0.0211	0.978, -0.0063, 0.0184	0.978,-0.0028, 0.0181	0.976, -0.0076, 0.0185	0.976, -0.0051, 0.0182
126 (II)	605	0.983, 0.0133, 0.0133	0.987, -0.0002, 0.0114	0.987, 0.0038, 0.0107	0.987, -0.0017, 0.0103	0.988, 0.0009, 0.0097
150 (III)	533	0.960, 0.0137, 0.0242	0.988, -0.0005, 0.0161	0.988, 0.0007, 0.0120	0.986, -0.0052, 0.0115	0.985, -0.0012, 0.0114
158 (III)	366	0.993, 0.0105, 0.0083	0.996, -0.0018, 0.0063	0.996, 0.0023, 0.0061	0.996, -0.0028, 0.0065	0.996, -0.0007, 0.0063
163 (III)	1536	0.993, 0.0080, 0.0091	0.995, -0.0044, 0.0076	0.995,-0.0015, 0.0076	0.994, -0.0067, 0.0081	0.995, -0.0039, 0.0075
172 (III)	371	0.982, 0.0096, 0.0131	0.978, -0.0011, 0.0134	0.978, 0.0031, 0.0136	0.974, -0.0010, 0.0148	0.972, 0.0018, 0.0148
185 (III)	1611	0.988, 0.0087, 0.0095	0.990, -0.0039, 0.0083	0.990,-0.0007, 0.0080	0.989, -0.0061, 0.0083	0.990, -0.0032, 0.0080
186 (III)	416	0.992, 0.0099, 0.0093	0.995, -0.0017, 0.0079	0.995, 0.0023, 0.0071	0.994, -0.0019, 0.0072	0.995, 0.0004, 0.0070
201 (III)	1162	0.979, 0.0090, 0.0135	0.979, -0.0040, 0.0133	0.979,-0.0005, 0.0132	0.975, -0.0057, 0.0144	0.972, -0.0027, 0.0151
202 (III)	764	0.992, 0.0146, 0.0094	0.996, 0.0011, 0.0075	0.996, 0.0043, 0.0076	0.996, -0.0007, 0.0080	0.996, 0.0017, 0.0081
214 (III)	543	0.989, 0.0147, 0.0143	0.995, 0.0014, 0.0145	0.995, 0.0049, 0.0094	0.992, 0.0002, 0.0116	0.983, 0.0023, 0.0168
228 (III)	289	0.976, 0.0095, 0.0159	0.984, -0.0024, 0.0136	0.984, 0.0023, 0.0123	0.985, -0.0029, 0.0120	0.986, -0.0004, 0.0112
Median	574	0.980, 0.0097, 0.0134	0.988, -0.0017, 0.0133	0.988, 0.0023, 0.0111	0.988, -0.0028, 0.0111	0.987, -0.0005, 0.0104

uncertainty of the Brewer AOD can then be written as

$$u^2(\text{Brewer}) = (2\sigma)^2 + 2u^2(\tau_o) - u^2(\text{UVPFR}) \tag{12}$$

The standard deviation σ of the Brewer-UVPFR difference for Brewer #185 at wavelengths between 310.1 and 320.1 nm contributes $(2 \cdot 0.01)^2$ to the total squared uncertainty. For the uncertainty of the ozone optical depth, we can use the same values calculated in Sect. 2.4. Finally, for the UVPFR, Carlund et al. (2017) reports a 2σ uncertainty between 0.04 and 0.02 in this range of wavelengths. All this points to a 2σ uncertainty between 0.04 and 0.01 for the Brewer AOD in the range of wavelengths from 310.1 to 320.1 nm. For 306.3 nm, the same calculation yields an uncertainty of 0.05. These values are fairly close to the ones found in our analytical derivation in Sect. 2.4.

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4   Discussion

Despite the overall good results shown in the previous section for our AOD determination method, there are multiple improvements that could be introduced in three different aspects: data processing, input data, and instrumental characterization. Regarding the data processing, note that besides the ozone-specific filters to remove mainly observations under cloudy condi-

5   tions, only one AOD-specific filter is included in our AOD algorithm. This AOD filter is based on the standard deviation of five consecutive observations and is expected to remove measurements affected by fast-moving clouds (Gröbner and Meleti, 2004). Further cloud-detection methods and filters to remove measurements under cloudy conditions should be devised and implemented to improve the quality of the Brewer AOD product. This will require a more extensive analysis of the AOD data from the whole EUBREWNET network.

10   With regard to the data used as input, first it should be noted that our AOD is currently produced in real time and as such uses the highest-quality real-time data available in EUBREWNET, namely the ozone level 1.5 product. Once the configuration of a Brewer instrument issued in one campaign has been validated in the next one, a level 2.0 ozone product is produced at EUBREWNET. We plan to implement an AOD product which will use these validated ozone values instead of the real-time data. A second point to consider is that currently the AOD algorithm uses the same pressure value used in the determination

15   of the ozone, which is the climatological value for the station where the Brewer operates. A 2σ uncertainty of 10 hPa in the pressure leads to ~ 0.01 added uncertainty in the Brewer AOD at the UV wavelengths, which is approximately half the uncertainty we have considered for the calibration. Using an in-situ measured pressure value would be thus advisable, although this would require adding further hardware and software infrastructure to the EUBREWNET network. A faster and easier to implement alternative would be to use the pressure data provided by any of the reanalysis products available, as in AERONET's

20   Version 2 Direct Sun Algorithm. Likewise, the ozone layer height is currently fixed at 22 km, also the same value used in the default ozone determination carried out by the Brewer. This could be improved by using a specific value for each latitude, as in AERONET's algorithm. Finally, note that we currently use data from wavelengths between 306 and 320 nm because they are available from the standard ozone measurements. However, it is planned to implement an AOD-specific measurement routine in selected Brewers of the EUBREWNET network which will allow to determine the AOD at longer wavelengths, including

25   340 and 354 nm. Note that extending the wavelength measurement range will likely require changes in our Langley calibration method, because ozone will stop being the largest contribution to the extinction. Besides the scientific interest, extending the measurement range will also allow for a better comparison with data from the AERONET network and satellite products from e.g. the Ozone Monitoring Instrument (OMI).

Regarding the characterization of the Brewer instruments, an important first point which requires further analysis is the

30   relation between the TOC and AOD calibrations, and more specifically which hardware changes in the Brewer instruments affect one or both retrieval related calibrations. Going into more specific details, our results indicate that improvements in the current polarization correction and taking into consideration stray light effects might be necessary. Our polarization correction is applied to data from all Brewer models taken at solar zenith angles greater than 55°. However, Carreño et al. (2016) have reported very recently different polarization corrections depending on the Brewer model. Furthermore, these authors have also

investigated the polarization at measurement angles below 35°, finding that a small but non-negligible correction might be also necessary. Further study is also necessary to characterize the uncertainty and correction needed by the stray light produced by the scattering on the single grating of Mk II and IV Brewer spectrophotometers (Karppinen et al., 2015). Finally, it should be noted that currently the temperature correction coefficients used in the ozone calculation are also used in the Brewer AOD
5   algorithm. These coefficients are relative to the value calculated for the shortest wavelength, but in the case of the AOD determination they should be absolute values because data for each wavelength is used individually. The determination of the absolute temperature coefficients in currently under study (Berjón et al., 2016).

5   Conclusions

In this work we have presented AOD results for the wavelengths between 306 and 320 nm, which correspond to the common
10   range for all Brewer models operating in ozone-measurement mode. Both historical and near real time data is already available at EUBREWNET's data server in these wavelengths, and could be used to determine the AOD at most sites taking part in the network. Furthermore, Mk IV Brewer models routinely measure in the visible range up to 450 nm, and Mk III models can reach 360 nm with specific measurement programs, so it would be possible to determine the AOD in a extended wavelength range, thus providing a more complete characterization of aerosols.
15   As we have shown, a well-maintained and calibrated Brewer instrument is capable of measuring AOD with a precision of 0.005 and an uncertainty of 0.04 in the UV range from 310 to 320 nm, the corresponding values for 306 nm being slightly worse, 0.01 and 0.05, respectively. Comparison between the data from Brewer and collocated Cimel instruments over a two year period shows that Brewer spectrophotometers are relatively stable and can be considered reliable AOD-determination instruments. Indeed, good maintenance carried out regularly at their operational sites and during intercomparison campaigns
20   might result in almost the same stability as in their usual ozone-measurement role.

The European Brewer Network can thus provide reliable aerosol data across a large area, from Tamanrasset (Algeria) to Kangerlussuaq (Greenland), in near real time and over an extended wavelength range. The availability of these data together with the ozone and UV irradiance one already available at its dataserver, would confirm the status of EUBREWNET as a key source of scientific information.

25 6   Data availability

The implementation of the present AOD algorithm in EUBREWNET's data server is expected for the upcoming months. Once functional, AOD data for the Brewer spectrophotometers calibrated at the intercomparison campaigns of the RBCC-E will be available in near real time.

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Appendix A: AOD equation in the internal Brewer space

Equation 4 is written in the standard terms used in optical depth calculations. However, the code used by Brewer spectropho-
tometers works in an internal, base 10 logarithmic space further multiplied by 10^4. If variables defined within this internal
space are used, the AOD equation for a specific wavelength then becomes

$$5 \quad \tau_a = \frac{1}{m_a} \left\{ \tilde{I}_0 - \tilde{I} - 10 \tilde{X}_o \tilde{k}_o m_o - \frac{p}{1013} \tilde{\tau}_{R0} m_R \right\} \frac{\log_e 10}{10^4} \tag{A1}$$

Note that the total ozone column $\tilde{X}_o$ is now in Dobson units, and that the ozone absorption coefficients $\tilde{k}_o$ are usually
provided divided by 10 (hence the 10 multiplicative factor in its term)

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

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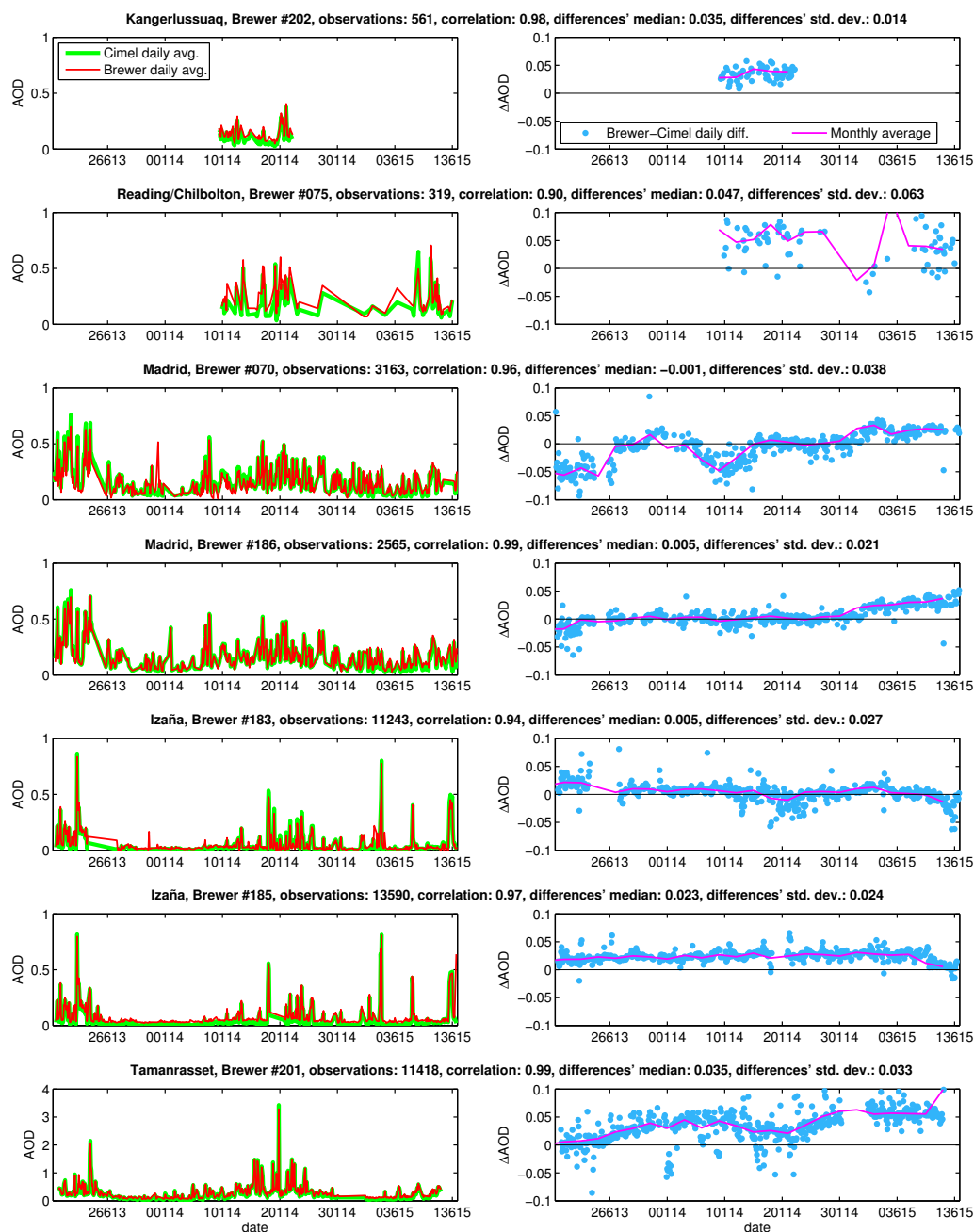
Figure 3. Brewer and Cimel AOD for the 2013–2015 period. AOD series shown on the left panels correspond to daily averages calculated from Brewer (red) and Cimel (green) observations within 1 minute. Daily (blue) and monthly (magenta) averages of AOD differences are shown on the right. For the Brewer we use the data for the longest measured wavelength at 320.1 nm, and for the Cimel, the 340 nm AERONET level 2.0 product extrapolated to 320 nm using the 340–440 Ångström exponent. Note that Brewer #075 operating at Reading is compared to the Cimel sunphotometer operating at Chilbolton. The y axis of the figures on the left go up to 1 in all cases except Tamanrasset, for which it reaches a value of 4. Dates in the x axis are written as *dddyy*, where *ddd* is the day number and *yy*, the last two digits of the year.
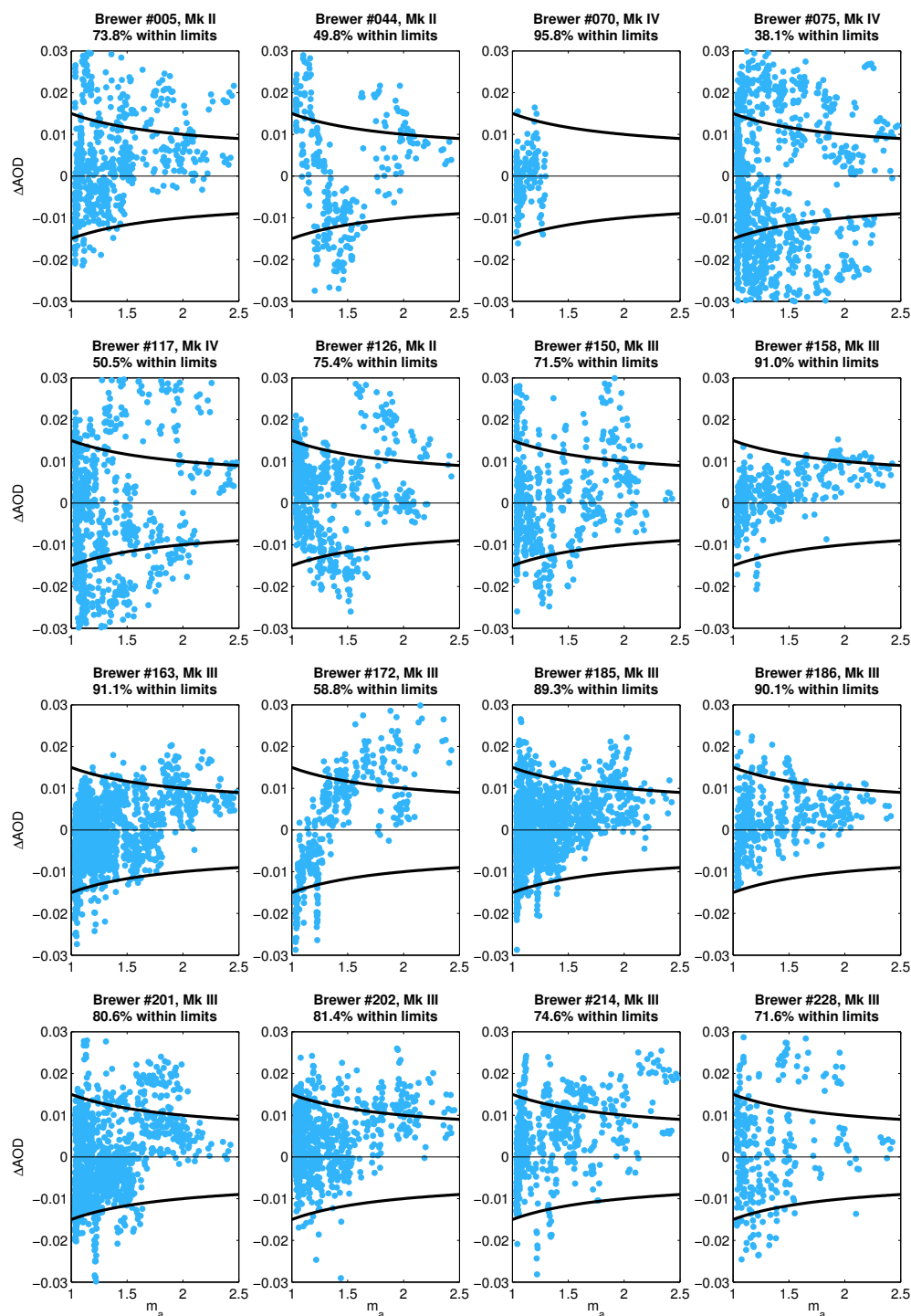
Figure 4. AOD differences, for observations within 1 minute at 313.5 nm, between the Brewer instruments and the UVPFR during the Tenth Intercomparison Campaign of the RBCC-E, plotted as a function of the aerosol optical airmass. The UVPFR data have been interpolated from that at wavelengths 311.3 nm and 317.5 nm using the Ångström relation. The WMO traceability limits for finite field of view instruments (Eq. 11) are shown as thick black lines.