Aerosol optical depth in the European Brewer Network: Reply to Anonymous Referee #1, RC1, 20 Nov 2017

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We thank the referee for their detailed comments on our manuscript. Below we include in italics a copy of their review and address their questions and suggestions.

Review of "Aerosol optical depth in the European Brewer Network" by López Solano et al.'

5 *The manuscript by López Solano et al is the result of a big collaborative work. It describes the algorithm and the processes used in EUBREWNET to retrieve AOD from the Brewer network, provides a quantitative estimation of the uncertainties, and lists a number of possible actions which could further improve the quality of the specific product. My main comment is that, although the manuscript is well structured and concise, linguistic corrections are necessary prior to its publication to ACP.*

In the following, there is a list of more specific suggestions minor comments.

10 *Abstract*

P1, L1-2: Add "," after the words "networks" and "time"

This sentence has been rewritten as follows:

"Aerosols play an important role in key atmospheric processes and feature high spatial and temporal variabilities. This has motivated scientific interest in the development of networks capable of measuring aerosol properties over large geographical areas in near real time."

P1, L4: According to the Eubrewnet webpage, the Eubrewnet network includes more than 50 instruments deployed not only in Europe, but from Patagonia, Argentina and Tasmania, Australia to Kangerlussuaq, Greenland. Why only 30 instruments are referred? Do you refer only to the currently calibrated instruments? Please be more specific.

This sentence has been rewritten as follows:

10 "In this work we present and discuss results of an aerosol optical depth (AOD) algorithm applied to instruments of the European Brewer Network. This network is comprised by close to 50 Brewer spectrophotometers, mostly located in Europe and adjacent areas, although instruments operating at e.g. South America and Australia are also members. Although we only show results for instruments calibrated by the Regional Brewer Calibration Center for Europe, the implementation of the AOD algorithm described is intended to be used by the whole network."

15 Furthermore, we have added a new paragraph (no. 5) to the Introduction:

"It should be noted that the RBCC-E provides calibration data for approximately half the Brewer spectrophometers integrated in EUBREWNET, and this paper is focused on these instruments. However, the present implementation of the AOD algorithm is intended to run directly on EUBREWNET's dataserver using any measurements and calibration data available. This would allow to extend the applicability of the present implementation of the AOD algorithm, with minor modifications 20 as needed, to the whole EUBREWNET network, because any other calibration data could be used besides that supplied by the RBCC-E. This includes calibrations transferred from other Brewer reference spectrophotometers, such as the one operated by International Ozone Services (Toronto, Canada, http://www.io3.ca/). Furthermore, preliminary work on the feasibility of using an Ultraviolet Precision Filter Radiometer (UVPFR) from the Physikalisch-Meteorologisches Observatorium Davos and World Radiation Center (Davos, Switzerland, https://www.pmodwrc.ch/) to calibrate Brewer instruments has also been carried 25 out (Carlund et al., 2017)."

P1, L9: Replace "aerosols" with "AOD".
Done.

30 *Introduction*
Some information regarding the importance of measuring the AOD in the UV, and especially in the UV-B region (where Brewers perform measurements), should be also added in the introduction. This would give the reader a better sense of the importance of this product. E.g., the interaction of aerosols with UV radiation, especially at lower wavelengths, is usually stronger and more complicated compared to the interaction between aerosols and the radiation at visible wavelengths, and yet 35 not fully understood (Bais et al., 2015: Ozone depletion and climate change: impacts on UV radiation). Thus, measurements

of the aerosol optical properties in the UV can improve the understanding of these interactions and help obtaining more information regarding the physical and chemical properties of aerosols. Furthermore, over several mid-latitude stations aerosols have found to be the main driver of the long-term changes of both, the (very important for the human health) UV and visible radiation.

5 We have added the following text at the end of the second paragraph of the Introduction:

"Although Brewer spectrophotometers can be used to retrieve AOD at longer wavelengths, in their standard operational mode most instruments can only produce data in the 300–320 nm range. This is nevertheless an important wavelength range to study, because the optical properties of aerosols in the UV-B are rather different from those in the visible and are yet not well known (see Bais et al. (2015) and references therein). It is also worth noting that the shortest wavelength provided by the

10 AOD product of the Aerosol Robotic Network (AERONET, https://aeronet.gsfc.nasa.gov/), one of the most used sources for ground-based aerosol data, is 340 nm, which makes Brewer AOD data in the 300–320 nm range a useful complement."

P2, L1: Use "such as" instead of "like"

Done.

P2, L4 – 6: Use "introduce large uncertainties" instead of "add a large uncertainty".

Done.

P2, L18: Again, I think that Brewers in Eubrewnet are more.

20 We have modified paragraph 3 in the Introduction as follows:

"[...] instruments integrated in EUBREWNET (COST Action ES1207, "a European Brewer Network", Rimmer et al. (2018), http://www.eubrewnet.org/cost1207), which is comprised by close to 50 Brewer spectrophotometers. Most of these Brewer instruments operate in Europe and adjacent areas, although some located farther away, for example in South America and Australia, have also joined the network."

25 Furthermore, we have added a new paragraph (5) to the Introduction, as already mentioned above.

P2, L28: "Further ... information". The specific sentence is not very clear. Please rephrase.

The sentence has been modified as follows:

"The multiple research programs carried out at IZO (Cuevas et al., 2015) provide additional information that may help to

30 carry out calibrations, such as e.g. forecasts of adverse weather conditions."

P3, L1: Replace "first give details" with "present the results of"

Done.

35 *P3, L2: I think that "estimate" would be more accurate than "derive"*

Yes, we agree, change done.

P3, L3: replace "in these Brewer instruments in" with "from these Brewer instruments for"
Done.

Method
P3, L9: Use "Methodology" instead of "method"
Done.

10   *P3, L13: Delete "used ... spectrophotometer"*
Done.

P3, L17: Use "performs" instead of "makes". Also, replace the phrase "and, through a well defined process, produces a TOC value" with "which, through a well defined process, are used to calculate TOC"
15   Done.

P3, L19: Replace the phrase "but ... work" with "the most relevant parts of which to the present study are highlighted in the following"
The whole sentence has been modified as follows:
20   "In the rest of this section we highlight the most relevant details for the present work of the instrument and the measurement process, see Kerr (2010) for further information."

P3, L20: Use "measures" instead of "detects"
Done.

P5, L8: Use "In addition to" instead of "Besides"
Done.

P5, L9: Use "we apply those" instead of "we also apply the ones"
30   Done.

P5, L10: Use "for" instead of "of"
Done.

35   *P5, L14 – 16: This sentence is not clear, please rephrase*

The text has been modified as follows:

"X_o: measured TOC in atm-cm. We currently use the real-time ozone level 1.5 product available at EUBREWNET's data server. However, instead of the Rayleigh coefficients supplied by default for all Brewer spectrophotometers, we use specific coefficients for each instrument determined during the RBCC-E calibration. These coefficients are calculated within the pre-scription of (Nicolet, 1984) and this modification in the Rayleigh contribution lowers the ozone value by approx. 0.003 cm, in agreement with the value reported by Kiedron and Stierle (2009)."

P6, L15: Re-write Eq. (6) so that all terms are in the same line.
Done.

P6, L27: I suppose that you add this last criterion (AOD st. dev. <0.02) to filter out the measurements performed under cloudy conditions (since these measurements are only partially filtered out by applying the TOC filters). Please add some more information.
We have added the following sentence at the end of this paragraph:
"Together with the criterion on the standard deviation of the ozone data described above, this ensures that measurements affected by clouds are removed."

P8, L7: I think that using the word "reliable" would be more accurate than using the word "correct".
Yes, that's right, word changed.

P9, L7: Replace "For the uncertainty" with "For the estimation of the AOD uncertainty due to the corresponding uncertainty in".
Done.

P9, L28: Use "dataset" instead of "data"
Done.

P9, L29: Use "from" instead of "for"
Done.

P9, L30: Add "which is" after "provided,"
Done.

P9, L31: Use "which is" instead of "this being"

Done.

P10, L6: Do you mean the corrections which are currently applied or the corrections which should be applied to reduce the effect of large FWHM? Please clarify.

The text has been modified as follows:

"Both Langley calibrations and AOD retrievals are affected by the finite FWHMs. Corrections which were used to reduce this influence, together with more detailed information about the UVPFR, are described by Carlund et al. (2017)."

Results

P11, L7: Do you mean the difference between the results for different filters?

Yes, that's right. The sentence has been changed to

"The difference between the results for different filters is $\sim 1\%$ at most"

P11, L8: I think that what you mean here is that the filter correction removes the greatest part of the effect of the different attenuation by different ND filters. Please re-write this sentence and make clear what you mean.

The sentence has been changed to

"[...] the filter correction applied to the data [...] removes most of the effect produced by the different attenuation of the different filters."

P11, L13: Use "by" instead of "due to"

Done.

P11, L15: Use "considered to be" instead of "taken as"

Done.

P11, L16: Delete "For comparison"

Done.

P12, L10: Use "for Brewers" instead "of Brewers"

Done.

P12, L11: Use "consider to be equal to" instead of "approximate by"

Done.

P13, L10: Delete "ones"

Done.

P13, L11: Use "toward" instead of "in"

Done.

Figure 3: The format of the date used at x-axis labels is a bit confusing. Using a format like mon-yy or at least something like "/" between DOY and year would be better.

We have added a slash between the DOY and the year.

10 *P13, L20: "with the lowest" instead of "the lowest"*

This part of the text has been rewritten as follows:

"As shown by the AOD series, there is clear correlation between the data of both instruments, with correlation coefficients above 0.90. The lowest correlation corresponds to the Reading/Chilboton data, which also shows the largest spread of Brewer-Cimel differences, in part due to the separation between the Brewer and Cimel sites, and in part due to sporadic data from the

15 Cimel sunphotometer."

P13, L26: Delete "it should ... Sect. 3.1" and add "(see Sect. 3.1)" at the end of the sentence.

The sentence has been changed to

"Regarding Brewer #070, in Sect. 3.1 it was found [...]"

P13, L28: Use "possible reasons" instead of "a possible reason"

Done.

P14, L13: Use "using" instead of "by"

25 Done.

Table 2: It seems to me that in this table you provide the 1-sigma instead of the 2-sigma standard deviation. Please double check.

Yes, in the tables we provide the standard deviation without any multiplicative factor because this is the most usual way of

30 presenting the data. Note that we always indicate in the text whether the $2sigma$ uncertainty has been used in the calculation of uncertainties. Regardless, to make it completely clear, the headers of Tables 1 and 2 now read

"[...] standard deviation (1σ) of differences"

Discussion

35 *P16, L2: "generally" instead of "overall"*

Done.

Conclusions

P17, L9: Replace "AOD results" with something like "the results of the AOD retrieval from Brewers participating in Eubrewnet".

The sentence has been changed to

"In this work we have presented results of the AOD retrieval for selected instruments participating in EUBREWNET"

P17, L16: Add "with" before "the corresponding"

Done.

P17, L21: Again, this area is possibly larger.

The sentence has been changed to

"The European Brewer Network can thus provide reliable aerosol data across Europe and adjacent areas (plus some more distant locations in e.g. South America and Australia) [...]"

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Aerosol optical depth in the European Brewer Network: Reply to Anonymous Referee #2, RC2 and RC3, 27 Nov 2017

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We thank the referee for their positive comments on our manuscript. Below we include in italics a copy of their review and address their suggestions.

This is a well-written article that does identify an important gapfor Brewer AOD calibration.The authors have modified
5 *the manuscripts in three aspects. Improvements of Brewer AOD data. Comparison Brewer AOD with other instruments. The uncertainty of Brewer AOD. There is an interesting finding in this research about Brewer AOD data. The paper would be significantly improved with the addition of some details.*

Section 2. Method

Line 15 and Line 24 Equation (1), (2) and (3) add λ into the equation, for example $I = I_O e^{-\tau m} \rightarrow I_\lambda = I_O \lambda e^{-\tau m}$

10 In Sect. 2.3 we have explicitly added the λ dependency to I and τ using brackets. For example, Eq. 1 is now written as

$$I(\lambda) = I_0(\lambda)e^{-\tau(\lambda)m} \tag{1}$$

However, we have dropped the explicit dependency on λ in subsequent sections to avoid encumbering notation.

Line 16 add I_λ is the direct solar irradiance at the ground doe each wavelength.

Done.

Section 2.3 AOD CALIBRATION OF Brewer instruments

Line 22 so we don't → so we do not

Done.

Aerosol optical depth in the European Brewer Network: Reply to V. Savastiouk, RC4, 4 Dec 2017

Javier López-Solano[1,2,3], Alberto Redondas[1,3], Thomas Carlund[4,5], Juan J. Rodriguez-Franco[1,3], Henri Diémoz[6], Sergio F. León-Luis[1,3], Bentorey Hernández-Cruz[2,3], Carmen Guirado-Fuentes[7,1], Natalia Kouremeti[4], Julian Gröbner[4], Stelios Kazadzis[4], Virgilio Carreño[1,3], Alberto Berjón[2,3], Daniel Santana-Díaz[2,3], Manuel Rodríguez-Valido[2,3], Veerle De Bock[8], Juan R. Moreta[9], John Rimmer[10], Andrew R. D. Smedley[10], Lamine Boulkelia[11], Nis Jepsen[12], Paul Eriksen[12], Alkiviadis F. Bais[13], Vadim Shirotov[14], José M. Vilaplana[15], Keith M. Wilson[16], and Tomi Karppinen[17]

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We thank the referee for his detailed comments on our manuscript. Below we include in italics a copy of his comments in RC4 and address his questions and suggestions.

Review of "Aerosol optical depth in the European Brewer Network"

5   *by Javier López-Solano et al.*

Vladimir Savastiouk

The paper, as I see it, is intended to present a near-real time aerosol optical depth (AOD) product based on the Brewer spectrophotometer direct-sun observations as it will be implemented in EUBREWNET. This is an extremely useful and scientifically important product.

10   *The AOD calculations within the Brewer community have evolved in the last 25 years and are well documented in scientific publications. These include numerous publications showing comparisons with other instruments.*

Indeed, the AOD retrieval by Brewer spectrophotometers is not a new topic, as stated in the Introduction just after the importance of aerosol studies is mentioned. Note also that the paper includes many references and comparisons to previous Brewer AOD studies, some of them written by coauthors of the present work.

5 *What is new for Europe and what should be the focus of the paper in my opinion is the idea of harmonization of the data through consistent, centralized processing and quality control at the EUBREWNET data centre.*

We agree with the referee and note that, to reach this goal of "harmonization of the data through consistent, centralized processing and quality control at the EUBREWNET data centre", we believe it is key to describe in a detailed and concise manner the algorithm implemented to retrieve the data. It's also important to demonstrate that this implemented algorithm produces 10 results of a reasonable quality.

A brief description of a very well known algorithm would be appropriate, however calling this "our algorithm" is a little misleading unless the paper clearly shows what is new in this implementation of the AOD calculations.

We apologize for any confusion caused by the expression "our algorithm" – we just used it as a short way to refer to the 15 specific implementation of the AOD algorithm implemented at the RBCC-E and presented in this work. To avoid further confusion, we now use "the AOD algorithm implemented at the RBCC-E" or similar expressions.

The paper describes very well the criteria for data selection and the corrections that will be implemented to the data. It also nicely shows how the RBCC-E calibrates their reference Brewers. I have some questions about this process though (these 20 are listed below). The paper confirms previously published findings that well-maintained and properly calibrated Brewers will provide reliable AOD data. Having EUBREWNET centralized data processing and quality control will be a great contribution to the scientific community.

Some general comments:

The authors should choose to either present the future AOD from Brewers that calibrated by RBCC-E only, and this would be 25 a sub-set of the data in the EURBEWNET database; or present and refer to all Brewers in the EUBREWNET but then clearly state that RBCC-E is only one of several agencies that provide calibrations for the Brewers in question. In fact, RBCC-E regularly reaches only about a half of the Brewers in the database, the rest are calibrated by others.

To make clear which instruments within EUBREWNET are considered in the present work, the following text has been added to the Abstract:

30 "In this work we present and discuss results of an aerosol optical depth (AOD) algorithm applied to instruments of the European Brewer Network. This network is comprised by close to 50 Brewer spectrophotometers, mostly located in Europe and adjacent areas, although instruments operating at e.g. South America and Australia are also members. Although we only show results for instruments calibrated by the Regional Brewer Calibration Center for Europe, the implementation of the AOD algorithm described is intended to be used by the whole network in the future."

35 Furthermore, a new paragraph (no. 5) has been added to the Introduction:

"It should be noted that the RBCC-E provides calibration data for approximately half the Brewer spectrophotometers integrated in EUBREWNET, and this paper is focused on these instruments. However, the present implementation of the AOD algorithm is intended to run directly on EUBREWNET's dataserver using any measurements and calibration data available. This would allow to extend the applicability of the present implementation of the AOD algorithm, with minor modifications as needed, to the whole EUBREWNET network, because any other calibration data could be used besides that supplied by the RBCC-E. This includes calibrations transferred from other Brewer reference spectrophotometers, such as the one operated by International Ozone Services (Toronto, Canada, http://www.io3.ca/). Furthermore, preliminary work on the feasibility of using an Ultraviolet Precision Filter Radiometer (UVPFR) from the Physikalisch-Meteorologisches Observatorium Davos and World Radiation Center (Davos, Switzerland, https://www.pmodwrc.ch/) to calibrate Brewer instruments has also been carried out (Carlund et al., 2017)."

For the network to be reliable some comments on sustainability of funding for RBCC-E and EUBREWNET database centre might be useful.

Rather than provide our own predictions on the future of the RBBC-E and EUBREWNET's dataserver, we have added a sentence on the background of the RBCC-E, so that the readers can draw their own conclusions:

"It should be noted that EUBREWNET's dataserver is currently maintained by the RBCC-E, which itself operates uninterruptedly since 2003 under the auspices of the WMO/GAW and the Spanish Agencia Estatal de Meteorología (http://www.aemet.es/)."

Following are line-by-line comments

Abstract: please be consistent in the usage of verb tenses: "algorithm to be used" means it is not yet used, "provides" means it is already working.

This part of the Abstract has been rewritten (see above)

P1 L7 the uncertainty does not include that from the air mass factor calculations, which can be significant. Please address this.

As stated in Sect. 2.4, the analytic derivation of the uncertainty presented in this paper is just an approximation, taking into account just three sources of uncertainty. The effect of the optical air mass has not been included because we only consider measurements up to a value of 3.5 in the optical air mass, and the uncertainty it introduces in this range is expected to be quite small, except perhaps for the shortest wavelength measured by the Brewer instrument, see Carlund et al. (2017) and the new reference Savastiouk and McElroy (2004).

We have added this explanation to Sect. 2.4 (see below).

P1 L8 Some of the "future improvements" can be easily implemented. Can you comment why you have decided not to do this now?

The current implementation of the AOD algorithm presented in this paper is intended to provide a base data level of reasonable quality, using calibration data which is immediately available, and in agreement with what has been discussed at meetings of EUBREWNET community.

P2 L17 "we have developed" is more like "we have implemented", no?
Changed.

P2 L21 to know that the accuracy is increasing you would have to know the true answer for TOC. How do you assess the accuracy?
We apologize for using the work "accuracy" incorrectly. The sentence has been changed to
"an increasing number of corrections to improve data quality"

P2 L23 this implies that RBCC-E is the only organization that provides calibration to the Brewers that are part of EU-BREWNET. Please address this. This comment applies to many parts of the paper and will not be repeated every time RBCC-E is mentioned.
This sentence has been rewritten as
"Also needed for the determination of the AOD is the data provided by the calibration of the Brewer instruments."
Furthermore, as already mentioned, a new paragraph (no. 5) with further information on the calibration providers has been added to the Introduction.

P2 L30 The wording suggests that calibration is transferred every year to all participating Brewers, while this is not the case. Please be more precise.
This sentence has been changed to
"This absolute calibration is transferred to participating instruments at international intercomparison campaigns"

P3 L10 suggest adding "by" between "section" and "providing"
Done.

P3 L24 it may not be extremely important, but there is another Brewer type, MK V, that has an 1800 l/mm grating with a FW3 and measures in the UV and the visible 600-650 nm range.
We thank the referee for pointing this out. Since there are no Mk V Brewers in EUBREWNET, to avoid confusion we have decided not to mention it. The sentence in P3 L24 has been thus changed to
"There are three types of Brewer instruments currently in use at the EUBREWNET network"

P3 L25 suggest removing "the effect of" since the double monochromator actually reduces the stray light, not just effects of it

Done.

5   *P3 L28 suggest "made up of" instead of "made up by". Also, suggest wording the rest of this sentence differently since it is only FW2 that adjusts the intensity, not both FW1 and FW2. Besides, you clearly say this in the next sentence.*

Text has been changed to

"The light subsequently passes through the fore-optics, which consists in a set of lenses to adequately focus the beam, an iris diaphragm, and two filter wheels. A ground quartz diffuser is located on the first filter wheel. The second filter wheel consists
10   of a set of five neutral density filter attenuators"

P3 L31 suggest "passing through the filter wheels". Also replace "spectrometer" with "monochromator"

Done.

15   *P4 L2 some of the characterization are obtained without a calibration campaign, e.g. DT, potentially TC, filters...*

This sentence has been rewritten as

"The Brewer retrieval of the TOC requires instrument characteristics which in some cases can only be determined by calibration experiments performed at 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)"
20   Since the TOC is not the main point of this paper and we provide references with further details, we don't think it's necessary to be more specific with regard of which calibration constants can only be determined at intercomparison campaigns.

P4 L7 functions must be plural

Changed.

P4 L8 Is it just one ETC that is determined?

Yes, for the ozone retrieval, a single ETC is determined. Its value can then be further modified by filter and stray light corrections, which are also determined during calibration.

30   *P4 EQ1 - this equation from 1983 is a concept that is impossible to use in practice: what is m? Some effective air mass factor? Using one variable for the product of tau and m that represents the slant total optical depth is better I think and can be expanded into its components with corresponding AMFs. Also, this equation is only valid for monochromatic light, but the Brewer measurements are clearly not that. Please either address this or reduce this whole description of the algorithm that is published elsewhere and only highlight your contribution (what is new).*

We could indeed remove the Beer-Lambert-Bouguer equation, because it is the basis for the operation of the Brewer (both for the AOD and ozone retrieval) and many other instruments, and as such it is very likely that this equation will be very familiar to the reader. However, we believe that introducing it helps to establish the notation and makes the derivation of all the expressions in Sects. 2.2 and 2.3 easier to follow. Furthermore, removing it would save almost no space – most of Sect. 2.2 is devoted to the description of the parameters used in the equations and how they are obtained, which we find is completely necessary to avoid any confusion when dealing with an algorithm used by many instruments.

Regarding the other comments of the referee, Eq. 1 is indeed valid for each of the wavelengths measured by the Brewer, which thus allows to retrieve the AOD in the whole wavelength range. To make it clear, in Sect. 2.2 we have added the explicit dependence on the wavelength in both text and equations, e.g.:

" [...]the well known Beer-Lambert-Bouguer equation (see e.g. Iqbal, 1983):

$$I(\lambda) = I_0(\lambda)e^{-\tau(\lambda)m}$$

where $I(\lambda)$ is the direct solar irradiance of wavelength λ measured at the ground[...]"

Regarding using a single variable in the exponent of Eq. 1, note that although we introduce two factors (τ and m) in this equation, we only expand their product in multiple contributions in Eq. 2, after we explain why we don't consider some other contributions.

Finally, regarding the meaning of m, it should be noted that, to avoid any confusion with the nomenclature used, we provide the specific mathematical expression used for the calculation of each of its components m_o, m_R, and m_a a bit later on the same section, see Eq. 5 and the accompanying text.

P5 L20 What is your rationale for using instrument-specific Rayleigh coefficients (which is not the standard now), but not improve the AMF calculations?

Rayleigh coefficients specific for each instrument are routinely obtained in the calibrations performed at the RBCC-E, and we have found that for some instruments they can have a noticeable effect on the TOC retrieval. Hence, it is natural that we also use them for the determination of the AOD.

We believe that changes on the expression of the optical air mass are indeed important, but should be discussed first by the whole EUBREWNET community – or perhaps even the whole world-wide Brewer community. In any case, our measurements are limited to a maximum optical air mass of 3.5, so we don't expect large errors in this range of air masses. See also the answers to further air mass-related questions below.

P5 L20 (continuation) Also, the formula for AMF is missing the instrument altitude, it's a lucky coincidence for IZO to have the ozone layer above the station close to 22km, but for Brewer #033, that is not far away, that is not true.

We currently only use measurements up to maximum optical air mass value of 3.5, so the error introduced by the omission of the instrument altitude in Eq. 5 is rather small. See also the answer to the next question.

P5 L28 this assumes that most of aerosol is in the troposphere. Is this a correct assumption?

We only include measurements up to an optical air mass value of 3.5, so the difference in altitude has a rather small effect. We have added the following text to the manuscript:

"Note that we only consider measurements up to a maximum optical air mass value of 3.5, so the exact altitude of the aerosol layer has a small effect on the the optical air mass. Thus for example, in the case of aerosols at sea level, the approximation $m_a \approx m_R$ introduces at most a $\sim 1\%$ error in the aerosol optical air mass."

P6 L4 suggest removing "one" from "each one of"

Done.

P6 L7 suggest using "separately" instead of "by separate"

Done.

P6 L18 "criteria" instead of "filters"

Changed.

P6 L22 Will it be appropriate to apply location-specific criteria for the AMF cutoff? Many Brewers are in high latitudes and if they are MKIII they canlikely successfully measure at higher SZA, no?

Yes, this is indeed a good suggestion that should be take into consideration by the members of the European Brewer Network. We have added the following text to the future improvements, see the first paragraph of Sect. 4:

"Furthermore, optical air mass limits specific to each Brewer model could be implemented. This would specially benefit Mk III instruments (which are largely free from stray light issues) operating at high latitudes."

P6 L25 suggest adding "test" between "lamp" and "filter"

Done.

P7 L3 "our Brewer" is, I assume, an IZO Brewer. Since not authors are from IZO I suggest refer to the reference Brewer as RBCC-E reference or similar

This part of the text has been hanged to

"with the RBCC-E reference Brewer"

P7 L5 Please describe what stable conditions are and how you objectively decide they are stable

The fourth paragraph in Sect. 2.3 describes the conditions in which the half-day Langley calibrations are performed, and which conditions they have to meet to be included in the final average. In particular, there are two conditions we use to determine if the Langley has provided good results and, thus, has been performed in stable conditions: the linear regression must

have a r^2 coefficient of determination above 0.995, and the resulting calibration constant must be within 1.20 times the median of the whole ensemble of calibration constants for the whole period. The results presented in the paper seem to indicate that these conditions produce a good selection of Langley results, in a rather objective way.

 P7 EQ7 - again, you cannot use EQ1 literally and make it linear before explaining what m is. Same in line 16.

We use the same notation through all the paper, so the meaning of m in Sect 2.3, and in particular in Eq. 7, is the same as in Sect. 2.2. As mentioned above, we believe that Eqs. 1, 2, and 5, plus the accompanying text, provide a good definition of m.

P7 L25 Do you (and how) monitor stability of the Brewer during the 1-2 months of calibration? If you average the results
 you assume the Brewer didn't change.

The Brewer instruments of the RBCC-E Triad are continuously and rigorously checked to ensure an optimal operational behaviour for the measurement of the TOC. This includes checks of each Brewer spectrophotometer individually (by means of internal tests on the standard and mercury lamp, and checks on dead time and operational voltages) and also comparisons between the three instruments. At this time, we rely on this TOC-specific checks to track the AOD stability, even though (as
 stated in the paper) we are aware that there are possibly some events that affect the AOD calibration but not that of the TOC. Furthermore, since we remove Langley results that deviate from the median value of the whole set of results (see one of the previous questions), we expect the resulting average to be a good representative of the whole period.

P7 L25 (continuation) Also, most points are collected at noon and only a few at larger SZA. Do you bin the data for Langleys?
 There are different ways to solve the problem of the uneven distribution in time of the measured data. In our case, in the fit we introduce dummy variables associated to each filter position (which are in turn related to the SZA). We can then perform a fit with data from all filters but obtain a single, common slope – the AOD, which is indeed assumed to be stable during the whole time. Note that the solution specific for each filter is then characterized by a different independent term, which we found to be negligible thanks to the filter correction performed before the fit, as mentioned in the paper.

P7 L28 and other places: please avoid using the word "usually". Try to either describe the conditions when this is true and/or provide frequency of this.

Indeed, the sentence in question does not clearly the describe this part of the calibration process, because in all the cases presented in the paper we have always performed the second, less-demanding calibration to characterize filter positions #0 and
 #1. The sentence has been rewritten as follows:

"Performing this Langley calibration procedure at IZO, we can only obtain calibration constants for just two filter wheel positions (#2 and #3), leaving another 4 positions without characterization due to a lack of measurements at this filter wheel positions."

We have also checked other occurrences of the word "usually" through the manuscript and made changes where necessary, retaining the cases where we don't expect any confusion.

P7 L29 maybe "filter wheel" is better here than "filter"

This part of the text has been changed to

"two filter wheel positions (#2 and #3), leaving another 4 positions without characterization. This includes filter wheel positions #0 and #1"

P8 L1 It is not clear why the difference will have lower uncertainty. If I take two measurements with same uncertainty then the difference between them will likely have double the uncertainty, no?

In the case of completely uncorrelated quantities, the uncertainty of the difference would indeed be the sum of the two uncertainties. However, in the case of correlated quantities, extra terms are included in the mathematical expression of the uncertainty (see e.g. GUM (2008)), and they might reduce the uncertainty. In the present case, there is certainly a correlation between the results of the calibration constants of two different filter positions, because they have been performed with the same data and method. The uncertainty of the difference is then expected to be reduced due to a cancellation of systematic errors associated with the two calibration constants (see e.g. Dunn, P.F.: Measurement and Data Analysis for Engineering and Science, CRC Press, 2010)

P8 L5 Why not use a matrix-based solution for all filters? It is described in cited literature and can easily be further improved.

In the ozone calibration, the calibration constant is split in two parts – the ETC and the so-called filter correction. In the AOD calibration procedure described in the paper, we obtain just one matrix of calibration constants, with one value for each filter and wavelength. We have considered splitting this matrix in the same way as in the case of the ozone, but there does not seem to be any clear advantage in doing it.

P8 L25 Uncertainty from AMF calculations is missing in the analysis.

As discussed in the question above, the analytic derivation of the uncertainty presented in this paper is just a simplification, as stated in the text. Its results are complemented by the uncertainty obtained from the comparison with other instruments, particularly the UVPFR. Regardless, we have modified the first paragraph of Sect. 2.4 as follows:

"We also assume no correlation between variables, and work within the approximation $m_a \approx m_o \approx m_R$. This latter approximation is reasonable within the maximum optical air mass value of 3.5 used in the present work, in which case the differences between the various optical air mass terms is $\sim 1\%$ at most. A more careful examination of the optical air mass is required in other cases, see Savastiouk and McElroy (2004)."

P17 L5 the TC are not always relative, especially in recent years' calibrations

This sentence is indeed specific to the RBCC-E calibrations, and it has been modified as follows:

"Finally, it should be noted that currently the temperature correction coefficients provided by the RBCC-E for the ozone are also used in the present implementation of the Brewer AOD algorithm."

5   *P17 L19 How do you plan to address the difficult question of objectively assessing whether the Brewers are "well maintained and calibrated"?*

This is indeed a difficult question, but a strategy that could work thanks to the large collaborative effort established by EUBREWNET would be roughly as follows. First, more long-term AOD comparative studies, both between Brewer spectrophotometers and also with other independently-calibrated instruments such as Cimels and UVPFR, should be produced.

10   Then, from the correlation of these AOD series with the maintenance records kept at the observation sites and the results of internal tests (standard lamp, dead time, ...), we expect it should be possible to determine which events result in a degradation of the AOD calibration. From there, guidelines for the maintenance of the Brewer instruments for AOD measurements could be established. For this strategy to produce reasonable and objective guidelines, a large amount of data should be analyzed and we believe EUBREWNET provides the necessary framework.

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Aerosol optical depth in the European Brewer Network: Reply to V. Savastiouk, RC5, 12 Dec 2017

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We thank the referee for his detailed comments on our manuscript. Below we include in italics a copy of his comments in RC5 and address his questions and suggestions.

There is no mentioning in the paper of the Sun-Earth distance in the AOD ETC transfer. It is implied that the AOD from the reference Brewer is corrected for this, but there is no word on which numbers are stored as ETC for the Brewer being calibrated. In other words, for this to work properly a common date has to be picked, say January 1 for convenience, and ETC are recalculated for that date for each Brewer. This is currently done by at least one calibration provider. It will be good if this paper also mention what is done at RBCC-E calibrations.

The raw counts measured by the Brewer being calibrated are corrected for the seasonal variation of the Earth-Sun distance as described in Sect. 2.2. Indeed all the corrections described in Sect. 2.2, as well as all the definitions of parameters introduced in that section, also apply to Sect. 2.3.

To make this clear, the text after Eq. 9 now includes the following sentence:

"Note that the counts per second I measured by the Brewer being calibrated include all the corrections described in Sect. 2.2."

References

Aerosol optical depth in the European Brewer Network

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Abstract. [..[1]]

Aerosols play an important role in key atmospheric processes and feature high spatial and temporal [..[2]]variabilities. This has motivated scientific interest in the development of networks capable of measuring [..[3]]aerosol properties over large geographical areas in near real time[..[4]]. In this work we present and discuss results of an aerosol optical depth [..[5]](AOD) algorithm applied to instruments of the European Brewer Network[..[6]]. This network is comprised by close to 50 Brewer spectrophotometers, mostly located in Europe and adjacent areas, although instruments operating at e.g. South America and Australia are also members. Although we only show results for instruments calibrated by the Regional Brewer Calibration Center for Europe, the implementation of the AOD algorithm described is intended to be used by the

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[2]removed: variability of aerosols make
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[6]removed: , which provides data in near real time of more than 30 spectrophotometers located from Tamanrasset (Algeria) to Kangerlussuaq (Greenland)

whole network in the future. 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 [..[7]]AOD.

1 Introduction

Concerning atmospheric physics and chemistry, it is well known that aerosols play an important role in processes [..[8]]such as 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 temporal variability of aerosols, and the different absorbing properties depending on their type, [..[9]]introduce large uncertainties 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 [..[10]]feasibility of using Brewer spectrophotometers, usually devoted to the measurement of the total ozone column (TOC) and UV irradiance, to determine the aerosol optical depth (AOD), see e.g. [..[11]]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); Savastiouk and McElroy (2004a, b); 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); Diémoz et al. (2016); Kumharn and Hanprasert (2016). Although Brewer spectrophotometers can be used to retrieve AOD at longer wavelengths, in their standard operational mode most instruments can only produce data in the 300–320 nm range. This is nevertheless an important wavelength range to study, because the optical properties of aerosols in the UV-B are rather different from those in the visible and are yet not well known (see Bais et al. (2015) and references therein). It is also worth noting that the shortest wavelength provided by the AOD product of the

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[9]removed: add a large uncertainty

[10]removed: capability of

[11]removed: 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 et al. (2016); Kumharn and Hanprasert (2016). Within the framework of COST Action ES1207, "a European Brewer Network" (EUBREWNET, Rimmer et al. (2017),

Aerosol Robotic Network (AERONET, https://aeronet.gsfc.nasa.gov/), one of the most used sources for ground-based aerosol data, is 340 nm, which makes Brewer AOD data in the 300–320 nm range a useful complement.

At the Regional Brewer Calibration Center for Europe (RBCC-E, Izaña Atmospheric Research Center, Agencia Estatal de Meteorología, Spain, http://rbcce.aemet.es/), 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 [..[12]]implemented an AOD algorithm [..[13]]for the instruments integrated in EUBREWNET (COST Action ES1207, "a European Brewer Network", Rimmer et al. (2018), http://www.eubrewnet.org/cost1207), which is comprised by close to 50 Brewer spectrophotometers. Most of these Brewer instruments operate in Europe and adjacent areas, although some located farther away, for example in South America and Australia, have also joined the network. [..[14]]One feature of the AOD algorithm implemented at the RBCC-E is that 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 [..[15]]available in near real time at EUBREWNET's dataserver (http://rbcce.aemet.es/eubrewnet). [..[16]]This dataserver allows for the harmonization of network data, providing four ozone product levels (three in near real time) with [..[17]]an increasing number of corrections to improve data quality (Rimmer et al., 2018). It should be noted that EUBREWNET's dataserver is currently maintained by the RBCC-E, which itself operates uninterruptedly since 2003 under the auspices of the WMO/GAW and the Spanish Agencia Estatal de Meteorología (http://www.aemet.es/).

Also needed for the determination of the AOD is the data provided by the [..[18]]calibration of the Brewer instruments. To carry out this task, the RBCC-E maintains a reference triad of Brewer spectrophotometers at the Izaña Atmospheric Observatory (IZO, Agencial Estatal de Meteorología, Spain, http://izana.aemet.es/), 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). [..[19]]The multiple research programs carried out at IZO [..[20]](Cuevas et al., 2015) provide additional information that helps to carry out calibrations, such as e.g. forecasts of adverse weather conditions. This absolute calibration is transferred [..[21]]to participating instruments at international intercomparison campaigns, held 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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[18]removed: instrumental calibration performed by the Regional Brewer Calibration Center for Europe (RBCC-E) during the annual intercomparison campaigns

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It should be noted that the RBCC-E provides calibration data for approximately half the Brewer spectrophometers integrated in EUBREWNET, and this paper is focused on these instruments. However, the present implementation of the AOD algorithm is intended to run directly on EUBREWNET's dataserver using any measurements and calibration data available. This would allow to extend the applicability of the present implementation of the AOD algorithm, with minor modifications as needed, to the whole EUBREWNET network, because any other calibration data could be used besides that supplied by the RBCC-E. This includes calibrations transferred from other Brewer reference spectrophotometers, such as the one operated by International Ozone Services (Toronto, Canada, http://www.io3.ca/). Furthermore, preliminary work on the feasibility of using an Ultraviolet Precision Filter Radiometer (UVPFR) from the Physikalisch-Meteorologisches Observatorium Davos and World Radiation Center (Davos, Switzerland, https://www.pmodwrc.ch/) to calibrate Brewer instruments has also been carried out (Carlund et al., 2017)."

The present work is organized as follows. [..[22]]The AOD algorithm implemented at the RBCC-E is described in Sect. 2. In Sect. 3 we [..[23]]present results of the calibration of selected Brewers carried out in 2013, and [..[24]]estimate the precision of these instruments for the AOD determination. Next, we check the stability of the AOD [..[25]]from these Brewer instruments [..[26]]for 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 with data of collocated Cimel sun-photometers as provided by [..[27]]AERONET. To close Sect. 3, we compare the Brewer AOD with the data produced by an [..[28]]UVPFR and derive the Brewer AOD uncertainty [..[29]]using data acquired during the Tenth Intercomparison Campaign of the RBCC-E. In Sect. 4 we discuss future improvements of our AOD algorithm, and in Sect. 5 we provide some closing remarks.

2 [..[30]]Methodology

We begin this section by providing a short overview of the Brewer spectrophotometer. Next, we describe the Brewer AOD equation used in [..[31]]the AOD algorithm implemented at the RBCC-E, 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[..[32]].

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2.1 The Brewer spectrophotometer

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 [..[33]]performs measurements of the direct spectral UV irradiances [..[34]]which, through a well-defined process, [..[35]]are used to calculate the TOC value. [..[36]]In the rest of this section we highlight the most relevant details for the present work of the instrument and the measurement process, see Kerr (2010) for further information.

The Brewer spectrophotometer [..[37]]measures 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 currently in use at the EUBREWNET network: the Mk II and Mk IV models are single monochormators, and the Mk III model is a double monochromator, a characteristic that reduces [..[38]]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, [..[39]]which consists in a set of lenses to adequately focus the beam, an iris diaphragm, and two filter wheels[..[40]]. A ground quartz diffuser is located on the first filter wheel. The second filter wheel consists of a set of five neutral density filter attenuators and guarantees that the detector is working in its linear regime. After passing [..[41]]through the filter wheels, radiation is then focused onto the entrance slit of the [..[42]]monochromator.

The Brewer retrieval of the TOC requires [..[43]]instrument characteristics which [..[44]]in some cases can only be determined by calibration experiments [..[45]]performed at 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 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

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instrument to instrument. The so-called "dispersion test" is thus used to determine the exact wavelengths of each instrument and its slit, or instrumental, [..[46]]functions. 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) 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):

$$I(\lambda) = I_0(\lambda)e[..^{47}]^{-\boldsymbol{\tau}(\boldsymbol{\lambda})\boldsymbol{m}} \tag{1}$$

where [..[48]]$I(\lambda)$ is the direct solar irradiance of wavelength λ measured at the ground, [..[49]]$I_0(\lambda)$ is the extraterrestrial (outside the atmosphere) solar irradiance, [..[50]]$\boldsymbol{\tau}(\lambda)$ 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 [..[51]]$\boldsymbol{\tau}(\lambda)$ 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 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 in the UV range can thus be written as

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

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

Solving for the aerosol optical depth [..[52]]$\tau_a(\lambda)$, Eq. 1 then becomes

$$\tau_a(\lambda) = \frac{1}{m_a}\{\log_e I_0(\lambda) - \log_e I(\lambda) - \tau_o(\lambda)m_o - \tau_R(\lambda)m_R\} \tag{3}$$

[..[53]]It should be stressed that Eq. 3 is wavelength dependent and [..[54]]valid for each wavelength λ measured by the Brewer spectrophotometer in the UV range. In this work we will consider only the five wavelengths between 306.3 and 320.1 nm which are measured by all Brewer models. The wavelength at 303.2 nm has a variable [..[55]]bandwidth which depends on the Brewer model, and [..[56]]other wavelengths above 320.1 nm are only routinely measured by Mk IV and V 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)

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

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. [..[57]]In addition to the usual corrections applied to the raw counts in the standard ozone data reduction (Kipp and Zonen, 2014), we also apply [..[58]]those described below. This requires the determination of some parameters which are specific [..[59]]for 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 [..[60]]dataserver. However, instead of the Rayleigh coefficients supplied by default for all Brewer spectrophotometers, we use specific coefficients for each instrument determined during the RBCC-E calibration. [..[61]]These coefficients are calculated within the prescription of (Nicolet, 1984) and this modification in the Rayleigh contribution [..[62]]lowers the ozone value [..[63]]by 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).

- m_o: ozone optical air mass, calculated as

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

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

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

- [..[64]]$\tau_{R0}(\lambda)$: Rayleigh optical depth at sea level following the prescription of [..[65]]Nicolet (1984), for each wavelength determined during the RBCC-E calibration process.

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

- m_a: aerosol optical air mass, which we approximate by m_R. Note that we only consider measurements up to a maximum optical air mass value of 3.5, so the exact altitude of the aerosol layer has a small effect on the the optical air mass. Thus for example, in the case of aerosols at sea level, the approximation $m_a \approx m_R$ introduces at most a $\sim 1\%$ error in the aerosol optical air mass.

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

- Filter correction, to remove the effect of the different attenuation of each [..[66]]filter 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 [..[67]]separately (see Sect. 2.3 next), so that any remaining effect of the different attenuations is taken into account in the calibration constants.

- 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):

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

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

To these corrected counts per second we also apply the data-quality [..[68]]criteria defined within EUBREWNET's level 1.5 ozone product (see http://rbcce.aemet.es/dokuwiki/doku.php for further details):

- 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).

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- Mercury lamp test 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. Together with the criterion on the standard deviation of the ozone data described above, this ensures that measurements affected by clouds are removed.

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 [..[69]]the RBCC-E reference Brewer spectrophotometer operating at IZO. The calibration transfer method is then used to calibrate other Brewer instruments operating simultaneously with [..[70]]the RBCC-E reference Brewer during the intercomparison campaigns.

Under the stable atmospheric conditions in which Brewer calibrations have to 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 to the data of a $\log_e I$ *vs.* m plot. Note that this equation is valid for each wavelength and filter position, so that multiple Langley fits [..[71]]are 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 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 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 [..[72]]do not expected any combination of the two air masses to introduce any significant changes.

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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 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

5 median of the whole ensemble of calibration constants for the whole period.

Performing this Langley calibration procedure at IZO, we [..[73]]can only obtain calibration constants for just two [..[74]]filter wheel positions (#2 and #3), leaving another 4 [..[75]]positions without characterization due to a lack of measurements at this filter wheel positions. This includes filter wheel positions #0 and #1, which are frequently 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

10 reference instrument, another Langley calibration is performed, but with less demanding limits – an extended optical [..[76]]air mass range from 1.1 to 5.5, and a lower tolerance of 0.9 for the r^2 coefficient of the linear regression. [..[77]]We have found that this less-demanding calibration [..[78]]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

15 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 intercomparison campaigns.

If the Brewer spectrophotometer to be calibrated is operating at the same place and simultaneously with a reference instrument already producing [..[79]]reliable AOD values, Eq. 4 can be solved for the calibration constant:

20 $$\log_e I_0 = \tau_a^{\mathrm{ref}} m_R + \log_e I + X_o k_o m_o + \frac{p}{1013} \tau_{R0} m_R \qquad (9)$$

Here, the τ_a^{ref} AOD value is provided by the reference instrument, and the remaining data are measured by the Brewer being calibrated. Note that the counts per second I measured by the Brewer being calibrated include all the corrections described in Sect. 2.2. 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

25 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 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.

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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 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 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 $m_a \approx m_o \approx m_R$. [..[80]]This latter approximation is reasonable within the maximum optical air mass value of 3.5 used in the present work, in which case the differences between the various optical air mass terms is $\sim 1\%$ at most. A more careful examination of the optical air mass is required in other cases, see Savastiouk and McElroy (2004b).

Taking into account all the above considerations, we write the AOD uncertainty as

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

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

- 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 $u^2(I_0)/I_0^2$ 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 [..[81]]estimation of the AOD uncertainty, 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 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

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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 [..[82]]~ 1 at all wavelengths, and we will consider a 1σ uncertainty of 5 hPa.

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 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. Solar 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 [..[83]]dataset currently available from Cimel sunphotometers, the cloud-screened and quality-assured version 2 level 2.0 product downloaded from the AERONET site (http://aeronet.gsfc.nasa.gov). We use the shortest wavelength provided, which is 340 nm, and the 340–440 Ångström exponent to extrapolate to 320 nm, [..[84]]which is 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 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 which were used to reduce this influence, together with more detailed information about the UVPFR, are described by Carlund et al. (2017). Where necessary for our

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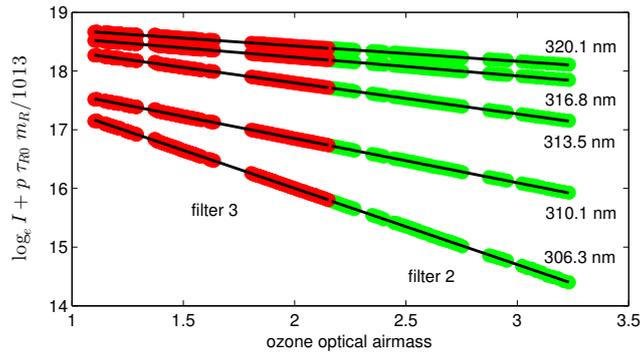
Figure 1. Langley plots for the five Brewer wavelengths between 306.3 nm and 320.1 nm, for measurements taken with filters 2 (green) and 3 (red) of Brewer #185 operating at IZO in the morning of May 31st 2013.

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 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 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

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 (Mk)	obs.	correlation, median of differences, standard deviation (1σ) of differences				
		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

constants for each wavelength and filter. The difference between the results for different filters is $\sim 1\%$ at most, showing that the filter correction applied to the data (see Sect. 2.2) [..[85]]removes most of the effect produced by the different attenuation of the different filters.

For the four longest wavelengths, the comparison between the independently-calibrated Brewers #183 and #185 in Table 1 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 [..[86]]by 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 same model and operate under the same conditions, so the standard deviations can be [..[87]]considered to be the precision (or instrumental repeatability) at the 1σ level, which ranges from 0.01 at 306.3 nm to 0.005 at 320 nm. [..[88]]Carlund et al. (2017) 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.

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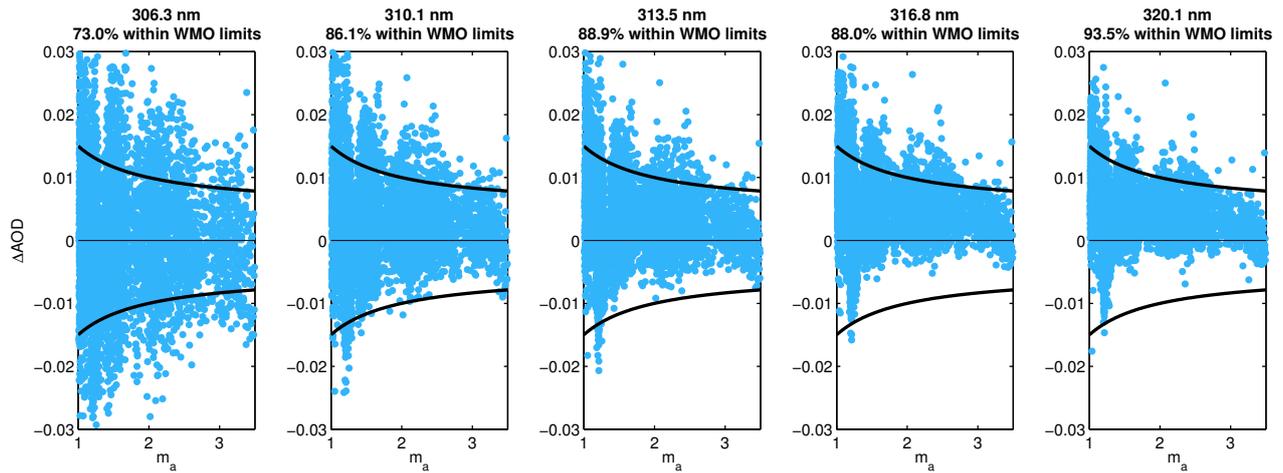
Figure 2. AOD differences between observations within 1 minute of the independently-calibrated Brewers #183 and #185, plotted as a function of the aerosol optical [..[89]]air mass. The WMO traceability limits for finite field of view instruments (Eq. 11) are shown as thick black lines.

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
5   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 [..[90]]for Brewers #183 and #185 as a function of the aerosol optical [..[91]]air mass (which we [..[92]]consider to be equal to the Rayleigh optical [..[93]]air mass, see Sect. 2.2) together with the WMO traceability
10   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
15   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

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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,
5 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 [..[94]]worse agreement with
10 the reference, particularly at the shortest measured wavelength. These two Brewer instruments are Mk IV models, while the others (including #183 and #185) are Mk III[..[95]]. 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 [..[96]]toward 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
15 (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
20 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[..[98]]. The lowest correlation corresponds to the Reading/Chilboton data, which also shows the largest spread of Brewer-Cimel differences, in part due to the separation between the Brewer and Cimel sites, and in part due to sporadic data from
25 the Cimel sunphotometer. 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, [..[99]]in Sect. 3.1 it was found to be one of the instruments
30 in worse agreement with the reference after the calibration transfer. The better behaviour of the collocated Brewer #186 in

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this 2-years comparison points to a bad calibration and/or to maintenance issues as [..[100]]possible reasons 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.

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 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

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 [..[102]]using the Langley plot method at IZO before the campaign, and this calibration was then transferred to the other Brewer spectrophotometers 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 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

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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 (Mk)	obs.	correlation, median of differences, standard deviation (1σ) of differences				
		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

reference Brewer #185 are fairly similar to those shown in Fig. 4, although in the comparison with the UVPFR the differences seem to increase with the optical [..[103]]air mass, 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.

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,

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the largest according to Carlund et al. (2017) is the ozone optical depth τ_o. Taking into consideration only this term, the 2σ 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
5   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.

10 **4 Discussion**

Despite the [..[104]]generally 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 conditions, only one AOD-specific filter is included in our AOD algorithm. This AOD filter is based on the standard deviation
15 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. Furthermore, optical air mass limits specific to each Brewer model could be implemented. This would specially benefit Mk III instruments (which are largely free from stray light issues) operating at
20 high latitudes.

    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
25 data. A second point to consider is that currently the AOD algorithm uses the same pressure value used in the determination 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 [..[105]]~ 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
30 implement alternative would be to use the pressure data provided by any of the reanalysis products available, as in AERONET's Version 2 Direct Sun Algorithm. Likewise, the ozone layer height is currently fixed at 22 km, also the same value used in the

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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 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 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 [..[106]]provided by the RBCC-E for the ozone calculation are also used in the present implementation of the Brewer AOD 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 [..[107]]results of the AOD retrieval for selected instruments participating in EUBREWNET. We have considered the wavelengths between 306 and 320 nm, which correspond to the common range for all Brewer models operating in ozone-measurement mode. Both historical and near real time data is already available at EUBREWNET's [..[108]]dataserver 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 [..[109]]an extended wavelength range, thus providing a more complete characterization of aerosols.

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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, with 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 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 [..[110]]Europe and adjacent areas (plus some more distant locations in e.g. South America and Australia) 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.

6 Data availability

The implementation of the present AOD algorithm in EUBREWNET's [..[111]]dataserver 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.

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 spectrophotometers 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

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

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.

Acknowledgements. This article is based upon work from the COST Action ES1207 "The European Brewer Network" (EUBREWNET), supported by COST (European Cooperation in Science and Technology). Part of this work has been developed within the IDEAS+ project of the European Space Agency, in collaboration with LuftBlick Earth Observation Technologies. This work has been supported by the European

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[110]removed: a large area, from Tamanrasset (Algeria) to Kangerlussuaq (Greenland) ,

[111]removed: data server

Metrology Research Programme (EMRP) within the joint research project ENV59 "Traceability for atmospheric total column ozone" (AT-MOZ). The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union. These activities have been partially developed in the WMO-CIMO Testbed for Aerosols and Water Vapor Remote Sensing Instruments (Izaña, Spain). We also acknowledge the support of the Ministry of Economy and Competitiveness of Spain and the European Regional Development Fund (ERDF) under the AEROATLAN project (CGL2015-66299-P). Thomas Carlund was supported through grant no. C14.0025 from the Swiss Staatssek-tretariat für Bildung, Forschung und Innovation (SBFI) within COST Action ES1207. J.J. Rodriguez-Franco gratefully acknowledges the support from COST Action ES1207 to conduct a short term scientific mission at the PMOD/WRC. C. Guirado-Fuentes acknowledges the funding from the POLARMOON project (CTM2015-66742-R) of the Spanish MINECO. Stratospheric ozone and spectral UV baseline monitoring in the United Kingdom is supported by DEFRA, The Department for the Environment, Food, and Rural Affairs, since 2003. We thank J.R. Moreta Gonzalez, J. Jeffrey, E. Cuevas, and B. Holben for their effort in establishing and maintaining the Madrid, Chilbolton, Izaña, Tamanrasset, and Kangerlussuaq AERONET sites. The AERONET sun photometers at the Madrid, Chilbolton, Izaña, and Tamanras-set stations have been calibrated within the AERONET Europe TNA, supported by the European Community-Research Infrastructure Action under the Horizon 2020 research and innovation program, ACTRIS-2 grant agreement No. 654109.

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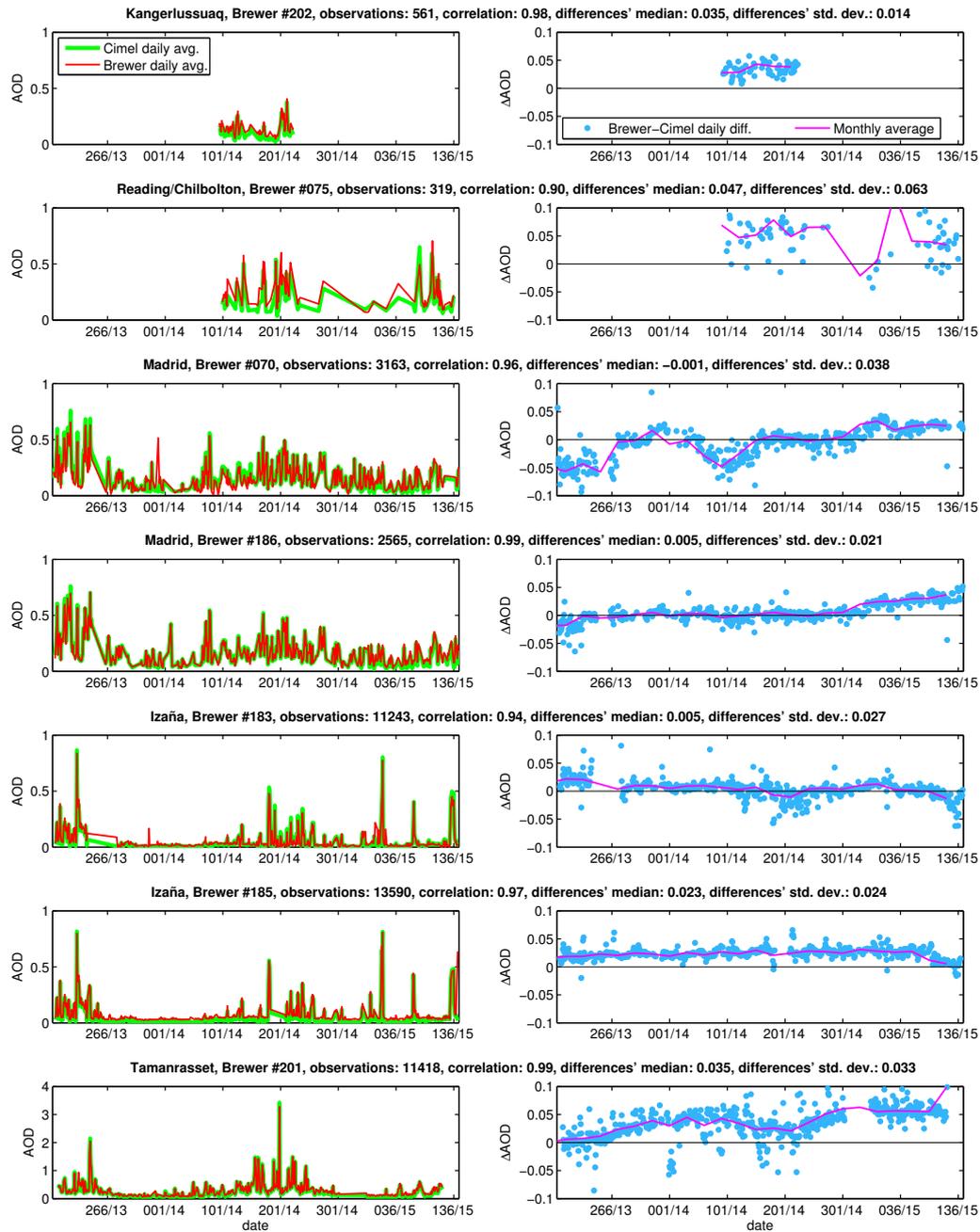
Figure 3. Brewer and Cimel AOD for the 2013–2015 period. AOD series shown on the left panels correspond to daily averages calculated from Brewer (red) and Cimel (green) observations within 1 minute. Daily (blue) and monthly (magenta) averages of AOD differences are shown on the right. For the Brewer 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 [..⁹⁷]*ddd/yy*, where *ddd* is the day number and *yy*, the last two digits of the year.
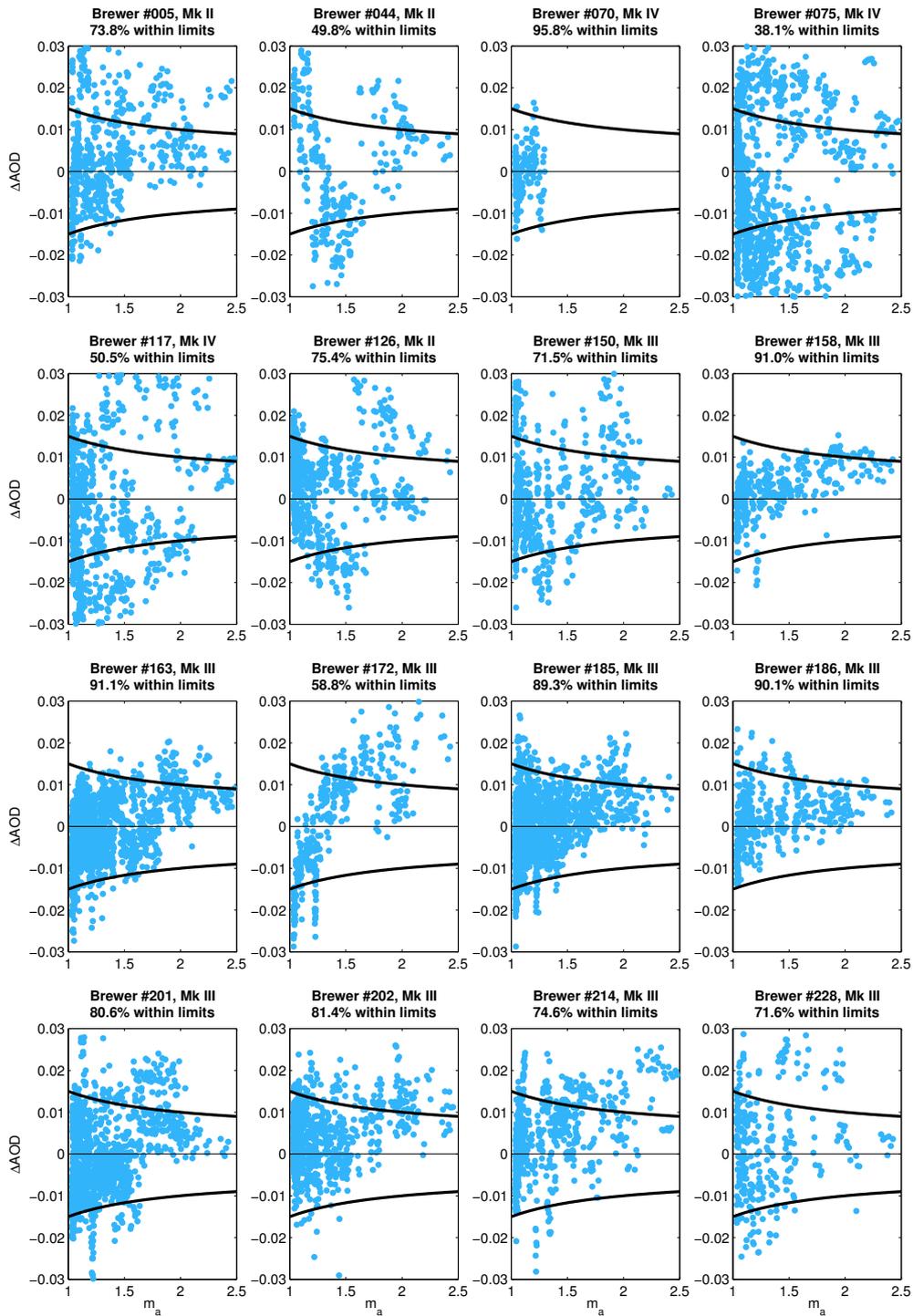
Figure 4. AOD differences, for observations within 1 minute at 313.5 nm, between the Brewer instruments and the UVPFR during the Tenth Intercomparison Campaign of the RBCC-E, plotted as a function of the aerosol optical [..[101]]air mass. The UVPFR data have been interpolated from that at wavelengths 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.