

Response to the Associate Editor

After the comments by the editor (bold letters) there is the corresponding answer.

Comments to the Author:

The authors have done a good job addressing the reviewers comments. The paper is ready for publication, after the following technical corrections have been made:

Page 11, lines 19, 20 (referring to the change-tracked, revised manuscript): Please add "wide" after 9°C and 10°C. This clarifies that you mean the width of TR2, not the center.

In Fig. 3: There are no data points for Brewer 214 below 10°C. Either add the data points, OR remove the red line, and also remove the discussion of Brewer 214 tests below 10°C.

In Fig. 7 g,h: Lidenberg should be Lindenberg.

In the supplement: a0 and a2 seem to be reversed, either in Eq. 5, or in the table header. Please correct, and please also double-check the numbers.

Reply

All comments by the Associate Editor have been addressed in the new revised version of the manuscript.

Response to Anonymous Referee #1

After each comment by the referee (bold letters) there is the corresponding answer. The page and the line numbers referred correspond to the new version with tracked-changes.

Brewer instruments were invented, designed and built to measure ozone column which is accomplished by means of ratio-metric measurement which to large extent is insensitive to instrument's optical throughput and PMT responsivity. The subsequent modification of the instrument to expand Brewer's application to measure irradiance seemed like a natural step, however was the stability of the instrument ever good enough to warrant it? This paper like several before it shows that w/o temperature corrections a long term monitoring of irradiance with Brewers will not produce data good enough to promote significant scientific discovery and precise RT model verifications. Perhaps it would be useful to provide a brief literature review highlighting the accomplishments (are there any?) of solar irradiance monitoring with Brewers.

Reply

A literature review highlighting the usefulness of the spectral UV measurements from Brewers has been added in the introduction (P2,L15 – P3,L2).

To correct the temperature effect the instrument must be characterized. The instrument can be treated like a black box w/o much understanding of how it operates and what is the mechanism of the temperature effect. One would expect that understanding the mechanism of the temperature effect would lead to a better methodology of temperature effect correction. Unfortunately, the characterization of Brewers fell on the shoulders of users who are forced to treat the instrument just as a black box because the manufacturers did not show much interest in solving the problem that in a better world would be their responsibility.

Reply

The present study is focused on improving the quality of the spectral UV measurements by suggesting an improved characterization and correction methodology compared to those already existing. Obviously, no operator has the ability to characterize the instrument perfectly and fully explain the effect of temperature. Thus, several assumptions have been made in the study while uncertainties still exist. As shown by the study, all Brewers have an instrument specific response to the temperature dependence, but a common method applicable to the standard processing of the Brewer has to be derived to correct for the error introduced by the temperature dependence.

The thermal equilibrium of instrument with its environment does not imply that it is isothermal. Different parts of the instrument will have different temperatures. The question should be posed whether the parametrization of the black box with a single temperature is sufficient. Should it be the PMT's temperature or the ambient temperature? Obviously the best result will be obtained if both temperatures are used in the parametrization. If the two temperatures are correlated single

temperature will suffice. However the perfect correlation is not the case because of the heater and heating from internal lamps, electronics and actuators. Plus there will be hysteresis.

In general case the temperature effect for each temperature range (TR1, TR2, TR3) should be modeled with the formula:

$$(1+A\Delta t_{\text{pmt}})(1+B\Delta t_{\text{ambient}})(1+a\Delta w+b(\Delta w)^2)$$

where $\Delta w = w - w_0$ is wavelength increment from the reference wavelength w_0 .

You have decided to collapse the coefficients A and B into a single one and neglect the $\Delta t_{\text{ambient}}$. What is the cost of this approximation we will not know from your data.

Reply

It is sure that the parameterization of the black box with a single temperature is not sufficient. As the reviewer already mentioned, a parameterization including the external and the PMT temperature would lead to improved results, though it would not solve the problem since the temperature gradients inside the instrument do not depend solely on the difference between the external and the PMT temperatures. Nevertheless, the only available information for a standard user is the PMT temperature for each UV spectrum. A discussion regarding the used parameterization has been added in section 3.3 (P15, L6-12)

Authors should be commended for recognizing that the temperature effect is different in different temperature ranges (TR1, TR2 and TR3). In previous studies of Brewers by Cappellani and Kochler (1999), Weatherhead et al (2001), Garane et al. (2006) and Lakkala et al. (2008) this feature was not recognized. Probably it was because some of the studies used the 50 W lamps that heats up the diffuser which ends up masking the temperature effect of the diffuser. Still in Fig. 2 of Cappellani and Kochler (1999) one can discern that the temperature coefficients are not constant through out the full range of temperatures.

Reply

Even when a 1000 Watt lamp was used for the characterization (e.g. in Garane et al), there were only few data points below $\sim 20^\circ\text{C}$ which were possibly considered to be outliers.

In Weatherhead et al (2001) data we see that for wavelengths greater than 325nm the temperature coefficients do not change with wavelengths and that all instruments have very similar (shapes) of temperature coefficients as function of wavelength differing only by wavelength independent offsets. This result may suggest that the wavelength dependence came from the nickel sulfate solar blind filter. But authors of the current study do not agree with it, right?

Reply

We have not suggested that the nickel sulfate filter is not responsible for the dependence of wavelength. Indeed, we believe that the NiSO₄ filter is responsible for part of the wavelength dependence (P12, L16-18). Changes have been made throughout the manuscript to make this clearer.

It is true that in Fig 1 of Weatherhead et al the results from most – not all - instruments are wavelength independent for wavelengths longer than 325 nm. However, there are instruments for which the dependence of wavelength is obvious (e.g. for Boulder, Everglades and Rocky Mountains).

Furthermore, analysis using a single trend for the entire range of temperatures may lead to misleading results, as, e.g., in Garane et al. (2006) where no wavelength dependence was found for B086. When the same results were re-analyzed by taking into account TR1, TR2 and TR3 the wavelength dependence was obvious.

Since part of the wavelength dependence is related to the transparency of the diffuser, the use of 50 Watt lamps by Weatherhead et al. may have also been responsible for not detecting any dependence of wavelength in their results. Additionally, the lamp tests for the study of Weatherhead et al were performed outside, leading to increased uncertainty in the results since the repeatability of measurements with 50W lamps is not very good due to the effect of changing environmental conditions (e.g., effect of the wind).

This confirms that the different patterns found between the three TRs are due to the change in the transmissivity of the Teflon diffuser.

This “this confirms” should be backed up with some illustration in this paper. Results of two tests: through diffuser and w/o diffuser.

Reply

Figure 5 and some relevant discussion were added in paragraph 3.2.

For the measurements through the window it was found that the change in the response/°C is wavelength dependent for both the single and the double monochromator Brewers, indicating that the dependence of wavelength might not be introduced by the NiSO₄ filter used only in the single monochromator Brewers as suggested by Garane et al. (2006).

Again this is speculative. Ylänntila and Schreder (2005) results suggest that Teflon introduces some wavelength dependence. The quantum efficiency of PMT's photocathode also has some temperature dependence that has a spectral component. Still nickel sulfite can't be acquitted from responsibility for wavelength dependence.

Anyway, Weatherhead et al (2001) results are not congruent with the present work.

Reply

What the reviewer says here is correct. The manuscript has been changed accordingly (P14, L5).

I presume that each measurement was preceded with mercury scan to correct the wavelength shift due to temperature. It should be stated.

Reply

The relevant information has been added in the manuscript (P10, L6-8).

However correcting the wavelength shift at 297nm does not completely correct the wavelength shift at 325nm or 360nm. This wavelength shift is due to (1) translation of slits away from the optical axis, (2) diffraction grating grooves density change and (3) micrometer screw expansion. The cumulative effect of wavelength change produces an apparent responsivity change, however this is not the true responsivity change as it depends on the spectral shape of the measured signal and it can't be applied to correct signal when measuring the solar spectral irradiance. It will be different for different lamps that have different spectral gradients $dI(w)/dw$, where $I(w)$ is lamps irradiance. The authors should estimate this effect. BTW, I do not think anybody was concerned with this effect in previous works. This spurious effect due to wavelength shift may account for part of wavelength dependence in the measured effect. Keep in mind that manufacturer's claims on wavelength stability specs can't be trusted. What impact this study will have on Garane et al. (2006) and Lakkala et al. (2008)? The current results are not congruent with the previous results, right?

Reply

The effect of wavelength shift was studied for B005 and B086. The results are discussed in section 3.3.6.

The Fig 5 is offered as a degree of proof that the correction will improve data quality. I have several issues here: (a) Did you force the points for the red curves to be zero at $t=25^{\circ}\text{C}$? It is too good to be just fortuitous.

Reply

Yes, the points were forced to be zero at 25°C . Now it is also written in the legend of figure 6.

(b) Why the "errors bars" in some cases for blue (after correction) are wider than for red? This is counterintuitive. BTW, what do the "error bars" represent?

Reply

As it is now explained in the manuscript (P20, L10) the error bars represent the 1σ standard deviation of the mean for each 10°C bin. There was an error which caused the large differences in the original version of the manuscript (for the corrected data one more year of measurements was used). Small differences are

still evident in the revised version, since the correction is not the same for both instruments at each temperature.

(c) The red curves should be closely approximated by the ratios of correction factors. I looked at the correction factors in the Supplement and looked at Fig. 3 and I do not get the same shapes as the red curves.

Reply

This comment is again correct. The plotted ratio in figure 6a (5a in the previous version of the manuscript) was reversed. Now it is corrected and is very close to what would be expected based on the results presented in Fig 3.

In Fig. 4 there is 315nm mentioned in the caption. It must be a mistake.

Reply

It has been corrected.

The red colors for 005 and 037 are too similar.

Reply

The color of the line for B037 has been changed (Fig 3).

Make the vertical scales of panels a and be the same, i.e., say 0.7 units in each case.

Reply

Now they are both 0.75 units (Fig 3).

Frankly I do not understand panels c and d. 1-sigma of what? Do you have enough points to justify talking about statistics? This has to be explained and justified or dropped.

Reply

The comment was correct. Panels c and d have been removed.

The paper is not easy to read. I had to go back and forth searching for info whether a given Brewer you were discussing is double or single and so on. I think a table with a list of Brewers, types, nickel sulfate yes or no, locations, temperature ranges, and coefficients (from Supplement) would help.

Reply

Table 1 which contains all the suggested information has been added in Section 3.

If you use the following formula

$$(1+A\Delta t_{\text{pmt}})(1+a\Delta w+b(\Delta w)^2)$$

the meaning and magnitude of coefficients A, a and b would be more easily readable. The coef A gives you general magnitude for w0 and a and b magnitude change with wavelength.

Reply

We think that the parameterization proposed here would be a bit more complicated to be reproduced by the Brewer operators after the instrument characterization. Thus we did not change the parameterization described in the supplement.

Also a method of measurements should be grouped in one place as apparently different Brewers were measured at different facilities with different equipment.

Reply

The relative information has been added in Table 1.

Fig. 3 shows that in some cases you did not have too many points. Also there are no data for TR1. Actually, what is the justification for having the same slopes for TR1 and TR3?

Reply

The (limited and uncertain) results that we have provide an indication that the slopes are not necessarily the same but similar (the differences are lower than the uncertainty of the derived slopes) in TR1 and TR3. Regarding the transmittance of the diffuser this assumption is verified in Fig 1 of Ylianttila and Schreder (2005). Measurements through the quartz window indicate that the different behavior in the three TRs is mainly due to the effect of temperature on the diffuser, thus we believe that this assumption is valid. Furthermore, the results presented in Figure 6 indicate that applying a correction based on this assumption improves the agreement between the instruments in TR1. Thus the correction is towards the right direction.

You are paying here a price for ignoring the ambient temperature. I feel uneasy about TR2 width in some cases. If ranges are really due to Teflon they should be similar among instruments.

Reply

The differences between the TR limits and ranges which were found for each case are estimated to be mostly related to the uncertainties in the characterization results and less to the characteristics of each instrument as it is now clearly stated in P8, L36. This issue is also discussed extensively in paragraph 3.3.

The issue is that the big change of coefficients between TR2 and TR3 can't be explained by data from Ylianttila and Schreder (2005) and the change should occur in narrower range.

Reply

In Figures 1-3 of Ylianttila and Schreder (2005) the change in TR2 ranges between 1 and 3% which is in agreement with what we found. Nevertheless in the same study it is stated that the change in transmissivity depends on the thickness of the used diffuser. Thus, if a particular Brewer is equipped with a thicker diffuser, compared to those used by Ylianttila and Schreder (2005), a larger change should be detected. The difference between the detected range of TR2 and the corresponding range detected by Ylianttila and Schreder (2005) is within the uncertainty limits described and justified in section 3.3.

Also that TR1 and TR3 are the same is not justified by Ylianttila and Schreder (2005).

Reply

This has been already answered above.

I do understand that dealing with these instruments is a real pain. I understand that characterizing temperature effects is not an easy task particularly when you have no right equipment and facilities. So I am not surprised that the paper leaves many unanswered questions. Nevertheless I will recommend it being published providing that authors make some effort to fix and explain some issues that are within their reach. I feel sorry for the author they are forced to engage in such unsatisfactory endeavor.

Response to Anonymous Referee #2

After each comment by the referee (bold letters) there is the corresponding answer. The page and the line numbers referred correspond to the new version with tracked-changes.

Brewer spectrophotometers have been used extensively in the past for measuring global UV irradiance. The high number of such instruments performing such measurements worldwide for very long periods, makes investigations like the one submitted valuable for the UV community.

Comments

Section 2

Since this paper is introducing a number of different instruments with different characteristics, including hardware, calibration facilities e.t.c. it would be essential for the authors to start this paragraph describing the main problem.

Reply

The problem is now described clearly in the introduction (P3, L16-P4,L7).

Temperature effect on Brewer measurements can be linked with PMT, diffuser difference in temperature compared with the ones during the standard calibration procedure, hysteresis effects, wavelength shift issues, other kind of stresses within the instrument.

The authors have to prioritize these effects and describe the methodology followed in order to eliminate or to investigate the effect of each of these factors.

Reply

In the revised version of the manuscript, information regarding the complexity of this issue has been added in the introduction and the beginning of Sections 2 and 3. In the introduction of Section 3 there was already information regarding what has been done to avoid large temperature gradients inside the instruments and to ensure the good quality of the characterization procedure in each case. More information has been added in the new version regarding what has been done in order to eliminate the effect of wavelength shifts (P10, L6-8). Furthermore, a more detailed description of the remaining uncertainties is now provided in paragraph 3.3.

A table with the instruments used together with some details on the method used for each one could be also useful for the reader.

Reply

Table 1 has been added in Section 3, which contains all the suggested information.

Section 3

“carried inside” ? you mean moved from sun measurements to the calibration room ?

Reply

Yes, the manuscript has been changed so this is clear (P9, L11).

Figure 4 shows that changes are not wavelength independent, at least for some instruments

Reply

Yes, this is clearly stated in both, the old and the new version of the manuscript (P12, L14-18).

The standard deviations of what ? how many measurements have been performed for each temperature, wavelength ?

Reply

The reviewer has a point here. The discussion for the standard deviation might be misleading. Thus, the relative figures and discussion have been removed.

In addition it is worth noted that only one instrument has a positive change with temperature in TR3.

Reply

This information has been added in P12, L8.

Are Ylliantilla results applicable to the Brewer using diffusers? Do some of the instruments use modified (that the Brewer initial) diffusers ?

Reply

Discussion relative to this question has been added in section 3.2 (P14,L16 – 25)

Section 3.2

“This confirms that the different patterns found between the three TRs are due to the change in the transmissivity of the Teflon diffuser.”

Based on this and figure 2: For measuring the instrument response the calibration is performed with the 1000W lamps in an environmental temperature of 25 degrees. Do this results imply that it is possible that, based on the above statement, the total duration of the normal calibration procedure may affect the calibration results ? (by having the diffuser heating up). Or most

importantly that sun and 1000W-lamp measurements are partly incompatible due to the different diffuser temperature inside the calibration room and outside, even if the ambient and calibration room temperatures are 25 degrees ?

Reply

Although the 1000 Watt lamps were not found to heat the diffuser (at least importantly), as was already discussed in section 2, the change of the room temperature during the characterization procedure may affect the results of the calibration. A more analytical discussion has been added in sub-section 3.3.3. As discussed in sub-section 3.3.1 the difference between the temperatures of the diffuser and the PMT is not important when the Brewer is illuminated by the sun. The relative uncertainties are already discussed in the same section.

Figure 4. I wonder how reliable are the results for wavelengths below 300nm given the low counts that the instrument is measuring using the 1000W lamp.

Reply

The level of the signal below 300 nm is of course lower than the signal at longer wavelengths, though for all the studied cases it is adequately high to give results of similar reliability to that of the results for longer wavelengths. For 1000 and Watt lamps the signal below 300 nm is much stronger than for the sun at the same wavelengths. We estimate that even the stray light effect on the measurements of single monochromator Brewers does not affect the results significantly.

Wavelength shifts for higher wavelengths is not out of the discussion even if a wavelength control/correction is performed at 297 (?) nm.

Reply

Relative discussion regarding the effects of wavelength shifts on the determination of the correction factors for the effect of temperature has been added (sub-section 3.3.6). Regarding the wavelength shift during field measurements, it may occur due to many reasons in addition to the effect of temperature. However, a wavelength correction is usually applied when the spectra are processed, which eliminates the greatest part of this later effect.

Conclusions

I understand that this is a mostly technical paper. But it would be interesting for the readers to demonstrate the brewer temperature effect a bit more clear and realistic. Reading this work I come to the conclusion that:

- a. since there is a heater in the instrument (and not a cooling system), we are mainly interested by the temperature effects from 10 to 40+ degrees**
- b. Brewer temperature is different from ambient temperature (most probably the instrument (out on the sun) temperature is higher in the hot days than the temperature (measured in the shadow).**

c. Temperature issues will affect mostly diurnal and seasonal global UV irradiance related investigations and not so much year to year trends.

Reply

All the above have been taken into account and relative discussion has been added (P21,L5 – P22,L4). However, (c) is partially true. Over high latitudes the mean temperature already changes, and is projected to change by more than 10 degrees until the end of the century. Such large changes might induce important biases in the study of the UV trends if the effect of temperature has not been removed from the spectra. Also there can be big differences (higher than 10 C degrees in mean temperature) between even subsequent years depending on the local weather conditions. The above are discussed in the paragraph of the Discussion and Conclusions section.

So since the study is including a number of instruments that have different response in the temperature change and also perform measurements in very different environments concerning actual ambient (and Brewer) temperatures, it would be interesting to show the actual global UV % deviations for each site based on the actual brewer temperature. Either on a daily basis using the daily temperature change or during the year using the temperature at the measurement performed at the maximum -all year long existent- solar elevation angle.

Reply

Figure 7 has been added in the manuscript.

Response to Anonymous Referee #3

Comment

This paper describes work which is part of a larger collaboration to characterise and standardise operation, data processing and calibrations of, the Brewer Ozone Spectrophotometer, under the umbrella of COST Action ES1207. It is well written and illustrates clearly the problems with UV absolute calibration and makes a very good effort to provide a solution to significantly reduce the uncertainties which arise due to temperature dependence of the measurements. It is also significant in that a Brewer network already exists which could provide a harmonised spectral UV network given sufficient study and rectification of the problems. In my opinion this paper provides a good starting point and should be published. However, I would hope that further studies will follow particularly with regard to long term stability in different climates and with different Brewer instruments.

Reply

We thank the referee #3 for his willingness to review this manuscript.

Temperature dependence of the Brewer global UV measurements

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1

2 **Abstract.** Spectral measurements of global UV irradiance recorded by Brewer spectrophotometers can be
3 significantly affected by instrument-specific optical and mechanical features, thus proper corrections are
4 needed in order to reduce the associated uncertainties to within acceptable levels. The present study aims
5 to contribute to the reduction of uncertainties originating from changes in the Brewer's internal
6 temperature, which affect the performance of the optical and electronic parts, and subsequently the
7 response of the instrument. Until now, measurements of the irradiance from various types of lamps at
8 different temperatures are used to characterize the instruments' temperature dependence. The use of 50
9 Watt lamps was found to induce errors in the characterization due to changes in the transmissivity of the
10 Teflon diffuser as it warms up by the heat of the lamp. In contrast the use of 200 or 1000 Watt lamps is
11 considered more appropriate because they are positioned at longer distances from the diffuser so that
12 warming is negligible. Temperature gradients inside the instrument can cause mechanical stresses which

1 can affect the instrument's optical characteristics. Therefore during the temperature-dependence
2 characterization procedure warming or cooling must be slow enough to minimize these effects~~allow all~~
3 ~~parts of the instrument to be nearly equilibrated~~. In this study, results of the temperature characterization
4 of eight different Brewer spectrophotometers operating in Greece, Finland, Germany and Spain are
5 presented. It was found that the instruments' response is changing differently in different temperature
6 regions due to different responses of the diffusers' transmittance. The temperature correction factors
7 derived for the Brewer spectrophotometers operating at Thessaloniki, Greece and Sodankylä, Finland
8 were evaluated and were found to remove the temperature dependence of the instruments' sensitivity.

9 **1. Introduction**

10 The Brewer spectrophotometer was developed in the 1970s and became commercially available in the
11 beginning of the 1980s (Brewer, 1973; Kerr et al., 1985b). They were initially designed to measure the
12 total columns of ozone (O₃) and sulfur dioxide (SO₂) and, towards the end of the 1980s, they were
13 modified to perform also spectral measurements of the global solar UV irradiance (Kerr and McElroy,
14 1995; Bais et al., 1996). Nowadays, more than 200 Brewer spectrophotometers are deployed worldwide.

15 Spectral UV measurements from Brewers have been used in a number of important studies which
16 highlighted the impact of the stratospheric ozone depletion until the mid-1990s on the levels of the solar
17 UV-B irradiance that reaches the earth surface (Fioletov et al., 2001; Kerr and McElroy, 1993; Lakkala et
18 al., 2003; McKenzie et al., 1999) and quantified the interaction between the solar UV irradiance, the earth
19 surface and the atmospheric components which mainly control its levels, such as ozone, sulfur dioxide,
20 aerosols and clouds (e.g. Arola et al., 2003; Bais et al., 1993; Bernhard et al., 2007; Fioletov et al., 1998).
21 Spectral measurements from Brewers have been used widely for climatological studies of biologically
22 effective UV doses (e.g. Fioletov et al., 2003; Fioletov et al., 2009; Kimlin, 2004), validation of satellite
23 products (e.g. Arola et al., 2002; Bernhard et al., 2015; Kazadzis et al., 2009) and validation of radiative
24 transfer models (Kazantzidis et al., 2001; Mayer et al., 1997). Lately, spectra from stations with long
25 measurement records have been used for the study of the changes of the solar UV irradiance, showing that
26 changes in air quality and climate have an important impact on its short- and long-term variability (De

[Bock et al., 2014; Fountoulakis et al., 2016; Fragkos et al., 2016; Lakkala et al., 2017; Simic et al., 2011; Smedley et al., 2012; Zerefos et al., 2012\).](#)

The uncertainty in the measurements of the total ozone column (TOC) is considered to be low, of the order of 1% (Kerr et al., 1985a), while the uncertainty in the measurements of the global spectral UV irradiance for wavelengths greater than 305 nm is estimated to ~~be about less than 5~~ ~6.5% for well maintained and calibrated instruments ([Bernhard and Seckmayer, 1999](#); Garane et al., 2006). However, insufficient correction for the effects of individual constructional and operational characteristics, e.g. stray light (Karppinen et al., 2014), dead time (Fountoulakis et al., 2016), cosine response (Antón et al., 2008; Bais et al., 1998) and temperature dependence (Garane et al., 2006; Lakkala et al., 2008), may lead to even larger uncertainties (Gröbner et al., 2006). Thus, better understanding of the instrument's characteristics and improvement of the characterization methods are necessary for keeping the uncertainties within acceptable limits (Seckmeyer et al., 2001). Improvement of the quality of the spectra is also essential for the detection of trends in the time-series of the measured irradiance (Weatherhead et al., 1998).

Changes in the internal temperature can affect the electronic, mechanical and optical parts, and subsequently the spectral response of each individual Brewer spectrophotometer (Kerr, 2010). [They have multiple and complex effects on the spectral response of the Brewer spectrophotometers. Existing studies \(e.g. Garane et al., 2006; Lakkala et al., 2008; Weatherhead et al., 2001\) suggest that temperature mainly affects the response of the photomultiplier tube \(PMT\) and the transmittance of the NiSO₄ filter used in the single monochromator Brewers. However, it is also possible that temperature affects the transmittance of the Teflon diffuser located at the entrance of the fore-optics \(Ylianttila and Schreder, 2005\) and also causes subtraction and contraction of the instruments' mechanical components which may affect their response. The characterization procedure \(and the subsequent correction of the spectra for the effects of temperature\) is quite difficult and uncertain for the following reasons: \(1\) Different components of the instrument are affected differently by changes in temperature, \(2\) specific components \(e.g. the PMT, the](#)

1 standard lamp or the heater) increase the temperature locally while they are operating, resulting in large
2 temperature gradients inside the instrument, (3) the characterization conditions (e.g. warming and cooling
3 rate) differ from the conditions during the instrument regular operation, (4) the lamps used for the
4 characterization may warm the diffuser and (5) Since these effects of temperature depend on the
5 individual characteristics of each ~~individual~~ instrument, Nevertheless, proper characterization is
6 necessary in order to take ~~them~~ the effects of temperature into account and avoid errors in the final
7 products.

8 The present study is focused on the evaluation of the characterization and correction methods for the
9 effects of temperature on the measurements of the global UV irradiance. Evaluation of the currently used
10 methodology for the characterization and correction of the direct irradiance and TOC measurements is out
11 of the scope of the present study. The internal temperature of the Brewer may change by up to about 20°
12 C in a day and by 40 - 50° C in a year. Existing studies suggest that the absolute response of the
13 instruments may change by 0.2 – 0.3% per 1 °C change of the internal temperature (Garane et al., 2006;
14 Lakkala et al., 2008). Thus, not accounting for temperature effects may lead to uncertainties or biases
15 greater than the desirable overall uncertainty in the measurements.

16 In contrast to the correction of TOC measurements for the effects of temperature, which is achieved
17 using a standard methodology (Kipp & Zonen, 2008; Savastiouk, 2005; SCI-TEC Instruments Inc., 1999),
18 there is no standard method for the characterization or the correction of the Brewer global UV
19 measurements. At several sites, 50, 200 and 1000 Watt tungsten – halogen lamps which are used to
20 monitor the stability and/or calibrate the Brewer spectrophotometers (e.g. Bais et al., 1996; Bernhard et
21 al., 2008; Heikkilä et al., 2016) are also used for the temperature characterization of the instruments.
22 These lamps are usually warm-colored, with a color temperature of ~3000K, thus they emit a significant
23 amount of infrared radiation. They are usually placed at vertical distances of 5, ~20 and 50 cm from the
24 diffuser, respectively, with the center of their filament aligned with the center of the diffuser.
25 Measurements are performed either inside, or outdoors at the regular operating position of the instrument,

1 | using various setups ~~at each~~which may differ between individual stations. In Cappellani and Kochler
2 | (2000), Siani et al. (2003) and Weatherhead et al. (2001) the temperature characterization of the global
3 | UV measurements was achieved by performing measurements of the irradiance from 50 Watt lamps
4 | outdoors, at different ambient temperatures. In two more recent studies (Garane et al., 2006; Lakkala et
5 | al., 2008) the reported temperature correction factors were derived by performing measurements with
6 | 1000 Watt lamps in the laboratory. Using the internal 20 Watt standard lamp (sl) (Kipp & Zonen, 2008)
7 | for temperature characterization may lead to errors since the emissivity of the lamp may be affected by
8 | the temperature effects on the lamp's power supply (Weatherhead et al., 2001). Furthermore, when the sl
9 | is on, it is possible that large temperature gradients exist inside the instrument. In addition, any changes in
10 | the transmittance of the diffuser are not taken into account when the internal lamp is used. All the above
11 | studies have reported that the Brewer's response is a monotonic linear function of temperature which may
12 | also depend on wavelength. However, Ylianttila and Schreder (2005) have found a sharp change in the
13 | transmittance of the Poly-tetrafluoroethylene (commonly known as Teflon) diffusers near 19 °C, usually
14 | ranging from 1% to 3%, which should also affect the response of Brewer spectrophotometers. This
15 | temperature behavior has not been confirmed so far for the diffusers used in Brewer spectrophotometers. ~~–~~

16 | In the present study we investigate the effects on Brewer diffusers when 50, 200 and 1000 Watt
17 | tungsten – halogen lamps are used for the characterization of the temperature dependence of spectral UV
18 | irradiance measurements. Additionally, the results of the characterization for the effects of temperature, of
19 | the single monochromator Brewer spectrophotometers with serial numbers 005, 030, 037, 078 (now on
20 | referred as B005, B030, B037, B078 respectively) and the double monochromator Brewer
21 | spectrophotometers with serial numbers 086, 107, 185 and 214 214 (now on referred as B086, B107,
22 | B185 and B214 respectively), are analyzed and compared to each other. These instruments are operating
23 | regularly at Thessaloniki, Greece (B005 and B086), Sodankylä, Finland (B037 and B214), Helsinki,
24 | Finland (B107), Lindenberg, Germany (B030 and B078) and Izaña, Tenerife, Spain (B185). Finally, the

application of the derived temperature correction factors is evaluated for the Brewer spectrophotometers operating at Thessaloniki and Sodankylä.

~~2.~~

3.2. Evaluation of the temperature characterization with external lamps

As listed in the Introduction, the temperature dependence can be due to different reasons. In this study, we investigated how the error due to the temperature dependence can be corrected using the only available information, which a standard Brewer user has: the PMT temperature. We study which method is best to characterize the Brewer (50 W, 200 W, 1000 W lamps) and which are the uncertainties related to this method. In the context of the present studyFor this purpose, measurements with 50 and 1000 Watt lamps were performed by B005, B086 and B214 inside the laboratory, while measurements with 200 Watt lamps were performed by B185 at the site of the instrument's regular operation.

~~were characterized in the laboratory using both, 50 and 1000 Watt lamps. Characterization was of B214 with 50 and 1000 Watt lamps was performed using the methodologies-methodology described in Garane et al. (2006) for B005 and B086, and in Lakkala et al. (2008) for B214. For each instrument,~~
Measurements with both types of lamps were performed under the same conditions, so that any differences in the results could be attributed to effects of the used lamps. The change in the response of B214 at various temperatures relative to 25 °C for 330 nm is presented in Fig. 1. While the results from the 50 Watt lamp indicate that the response of the Brewer decreases linearly with temperature, the 1000 Watt lamp reveals a sudden increase in the response for temperatures between ~13 and 22 °C, and for higher and lower temperatures the pattern is similar with the 50 Watt lamp. Similar results are obtained for all wavelengths. The characterization of B005 and B086 with 50 and 1000 Watt lamps yielded patterns which were also similar with those presented in Fig 1. It should be noted that the characterization procedure followed for these two instruments (Garane et al., 2006) is slightly different compared to that of Lakkala et al. (2008) and for all three instruments.

1 The different behavior of the Brewer's temperature dependence could be attributed only to the
2 different thermal effect of the two lamps on the diffuser, taking into account that although weaker, the 50
3 Watt lamps are placed much closer to the diffuser. In order to investigate further this effect, the
4 temperature of the diffuser of the two Brewers operating at Thessaloniki was measured with a
5 VOLTCRAFT IR 260-85 infrared thermometer while each lamp was turned on. The lamps were
6 positioned at the same distances and with the same configuration as in the absolute calibration and the
7 temperature characterization tests. Initially, only the cover of the Brewer that holds the diffuser with the
8 dome was used and the temperature was measured by pointing the IR thermometer towards the center of
9 the diffuser from beneath, i.e. from the side where normally the fore optics of the Brewer are located. The
10 temperature of the diffuser was measured when it was not illuminated by the lamp. The lamp was either
11 moved away (50 Watt lamps) or the radiation was blocked (1000 Watt lamps) before each measurement.
12 This procedure was repeated several times for about 90 mins. During the test the ambient temperature in
13 the vicinity of the diffuser was also monitored. The temperature of the diffuser and the ambient as a
14 function of time are presented for B005 in Fig. 2a and 2b, respectively for the 50 Watt and the 1000 Watt
15 lamps. The behavior of B086 is almost identical to that of B005.

16 For the 50 Watt lamp (Fig. 2a) the temperature of the diffuser increases fast, by about 20 °C in the
17 first 30 mins, and thereafter it remains relatively stable, while the ambient temperature remains almost
18 stable. Moreover, measurements at different parts of the diffuser's surface while it was illuminated
19 revealed inhomogeneities of 5-6 °C. These findings suggest that 50 Watt tungsten-halogen lamps are not
20 suitable to characterize the overall temperature dependence of the Brewer, since they affect the
21 temperature and eventually the throughput of the diffuser.

22 For the 1000 Watt lamp, the temperature of the diffuser increases gradually by 5 – 8 °C following the
23 almost identical increase of the ambient temperature in the dark room (Fig. 2b). This suggests that the
24 lamp does not affect significantly the temperature of the diffuser, or at least no more than it affects the
25 ambient temperature.

For the 1000 Watt lamps we tested also an alternative configuration: The whole instrument (not only the cover) was placed under the lamp and the temperature of the diffuser was recorded by pointing the IR thermometer towards the upper surface of the diffuser after removing temporarily the quartz dome. During each measurement the radiation of the lamp was blocked. Then the dome was restored to its position and the lamp was unblocked to illuminate the diffuser until the next measurement. Each measurement (from blocking to unblocking the light) did not last more than ~1 min. During this test, in addition to the ambient temperature of the dark room, the temperature at the ~~photomultiplier tube (PMT)~~ ~~of the Brewer~~ was also recorded using a built-in thermistor. The measurements collected from this test are presented in Fig. 2c. As with the cover only, the temperature of the diffuser is not affected by the lamp's radiation and increases gradually following the increase of the temperature at the PMT. This suggests that the temperature at the PMT could represent both the internal temperature of the Brewer and that of the diffuser for the characterization procedure. However, during regular outdoors operation the temperature of the diffuser may differ significantly from the temperature of the PMT, as discussed later.

The slower increase of the diffuser's temperature compared to Fig. 2b is possibly explained by the fact that the lower surface of the diffuser is not exposed to ambient air, protected by the cover and the body of the instrument. Finally, it may be concluded that the 1000 Watt lamps, or any type of lamps that are positioned adequately far from the diffuser to prevent direct heating, can be safely used to characterize the temperature response of the Brewer.

At the station of Izaña, the temperature of the diffuser of B185 was recorded using an infrared sensor while a 200 Watt lamp was placed above the diffuser. In this case the sensor was adjusted inside the instrument, aiming at the bottom surface of the diffuser and its signal was recorded by a data logger which was also placed inside the instrument. The setup of the 200 Watt lamp is the same as that used for the regular monitoring of the instrument's stability and for the temperature characterization. The measurements were performed at the location of regular operation of B185. As for the Brewers in

Thessaloniki, no significant change of the temperature of the diffuser was detected while it was illuminated by the 200 Watt lamp.

The lamps used at other sites usually have similar characteristics with those used at Thessaloniki, Sodankylä, and Izaña, and even if they are not supplied from the same manufacturer they are expected to have similar effects on the temperature of the diffuser.

4.3. Characterization for the effects of temperature

The results presented in this section were obtained by characterizing the temperature sensitivity of the instruments' response in the laboratory. Several instruments were tested following slightly different procedures according to facilities available in each station. ~~Since the temperature of the Brewer's diffuser is not recorded systematically, the~~ The temperature of the PMT which is regularly monitored has been used ~~to derive the temperature correction factors.~~ In Thessaloniki, the B005 and B086 were moved from the site of the instruments' regular operation ~~carried~~ inside the calibration room during a cold day and irradiance measurements of a 1000 Watt lamp were performed as the room temperature and the internal temperature of the instruments ~~was~~ were gradually increasing. The increase in temperature was slow enough to ensure that the temperatures of the room and the instrument are equilibrated (Garane et al., 2006). In Sodankylä ~~and Helsinki~~, B037, B107 and B214 were also carried inside the laboratory, where irradiance measurements were performed similarly as during a calibration (Lakkala et al. 2016), but the temperature of the Brewer was slowly increased or decreased using an air-blower system built for the specific purpose (Lakkala et al., 2008). Before each measurement, the temperature was stabilized and remained constant during the measurement. In Lindenberg, B030 and B078 were placed in a chamber wherein the temperature was increased or decreased slowly and scans were performed using a 200 Watt lamp after the temperatures outside and inside the instrument were fully stabilized and temperature gradients were practically zero. ~~In Izaña,~~ B185 was also placed in a chamber at the facilities of PTB and the temperature characterization was obtained similarly as for B030 and B078 (Berjon ~~and Redondas et al., 2017~~ 2016). In all the above cases the current of the lamps was constant within less than 1 mA (8 A for

the 1000 Watt lamps and 6.3 A for the 200 Watt lamps) during measurements. The spectrum of the used lamp was measured before and after the characterization of B037, B107 and B214 to ensure that neither the response of the instruments nor the characteristics of the lamp changed during the characterization procedure. For the remaining five Brewers the signal of the lamp was recorded using either a photodiode (B005, B086, B030 and B078) or a silicon detector and a CCD spectrometer (B185) to ensure that the detected changes are not due to changes of the lamp's emission. In all cases a line (the 297 or 302.15 nm line depending on each instrument settings) of the internal Hg lamp (Kipp & Zonen, 2008) was scanned before measurements at specific temperature to ensure wavelength stability. All measured spectra were corrected for the effects of the dark signal and the dead time, and smoothed by a 3-point moving average filter to suppress the noise. Finally, the change of the instrument's response with respect to temperature was calculated.

Brief information regarding the site of regular operation and the characteristics (type, single or double monochromator, NiSO₄ filter or not) of each instrument is summarized in Table 1. A short description of the place and the method of characterization and the temperature range are also provided in the last two columns.

~~4.1.~~

~~4.2.~~3.1. Temperature correction factors for different Brewers

Analysis of the measurements of the eight Brewer spectrophotometers revealed three temperature ranges (TR) with different patterns in the temperature response: Low (TR1), around 19 °C (TR2) and high (TR3). In these ranges spectral measurements of the global UV irradiance should be treated differently in order to correct for temperature effects. In each range the temperature dependence of the instrument's response can be described to a good approximation by least-squares linear fit. Although for each individual instrument the slopes of the linear fits change with wavelength, the limits of the temperature ranges are wavelength independent. Indicative results for 315 nm and for all the eight instruments are

presented in Fig. 3. The limits were estimated by eye and then the linear fit that describes the change in response for each TR was calculated.

Measurements below 10 °C, which provide information for TR1, were possible only for three of the instruments (specifically for B078, B185 and B214). At this point it should be noted that Brewer spectrophotometers are equipped with a heater which is automatically turned on when the internal temperature drops below a specific limit, either 10 °C or 20 °C (Kipp & Zonen, 2008). Thus, even for ambient temperatures below zero, the internal temperature does not usually drop below 0 °C and 10 °C respectively. For the same reason it is difficult to perform measurements for such low internal temperatures during the characterization procedure. For B185 and B214 the heater threshold has been set to 20 °C while for the other six instruments it is set to 10 °C. To achieve low internal temperatures for the first two the heaters were disconnected during the characterization procedure. For B185 two sets of measurements were performed: one for internal temperatures ranging from -2 to 24 °C and one for temperatures between ~13 and 50 °C. The measurements of the two sets were analyzed independently. Prior to analysis, the measurements were normalized to the highest common temperature of the two sets (24 °C). For all the other instruments the measurements were normalized to the 20 – 30 °C means.

The results presented in Fig. 3 verify that the response changes differently in the three TRs. However, the limits of the different TRs were not found to be the same for all instruments and even for the same instrument they may differ if the characterization is repeated under different conditions. For example, for the two sets of B185 TR2 was respectively 13 and 9 °C wide, i.e. about 4 °C different. For B078 and B214 the TR2 was 6 and ~~10-9.5~~ °C wide respectively. For the remaining five instruments, for which it was not possible to determine clearly the boundaries of TR2, this was assumed to be 10 °C~~-. This approximation was made based since this range was found close to ~10 °C on the results~~ for B078, B185 and B214~~, as well as on the results of Ylianttila and Schreder (2005)~~. The limit that separates TR1 from TR2 ranges between 12 °C (for B214) and 16 °C (for B078), while the limit that separates TR2 from TR3 ranges from 20 °C (for B078) to 26 °C (second set of B185). The differences between the TR limits and

ranges which were found for each case are estimated to be mostly related with the uncertainties in the characterization results and less with the characteristics of each instrument.

For B078, B185 and B214 the differences between the slopes of the linear fits for TR1 and TR3 are small, ~~below the 1 sigma uncertainties of the regressions (see Fig. 4 for TR3).~~ And although the slopes for TR1 were derived either from a limited number of measurements (B078, B214), or with the internal heater turned off, which does not represent realistic operational conditions (B185, B214), the results provide a strong indication that the slope calculated for TR3 can be also used for the correction of measurements within TR1, without inducing important errors. It is noteworthy that for seven of the eight studied cases the response is increasing in TR2 and decreasing in TR3, while increase in both, TR2 and TR3, was found only for the case of B005.

In Fig. 4, the calculated slopes ~~and the corresponding 1 sigma uncertainties of the regressions~~ are presented as a function of wavelength for TR2 and TR3. For B185 only the results from the second set of measurements (for higher temperatures) are presented. For all cases the dependence from wavelength is described satisfactorily by a 2nd degree polynomial. With the exception of B185 (TR2 and TR3) and B030 (TR2), for all the other instruments the percentage change of their response for °C increase in temperature increases with wavelength. The dependence of the slope from wavelength is stronger for the single compared to the double monochromator Brewers, possibly due to the presence of the UG11 – NiSO₄ filter combination at the entrance of the PMT of the former. The change of the response in TR2 ranges from ~0%/°C (for B078) to ~0.6%/°C (for B005). In TR3 the change of the response ranges from – 0.3 to +0.2% for different instruments and wavelengths. ~~Since the correction factors for different instruments have been derived from different number of data points, the standard deviation presented in panels 4c and 4d cannot be used as a criterion for the comparison of their quality.~~

1 Analytical description of the methodology that should be used for the correction of the global UV
2 irradiance measurements, as well as the calculated correction factors for each of the eight Brewers can be
3 found in the supplement.

4 —The role of the diffuser

5 4.3.3.2.

6 Comparison between the patterns shown in Fig. 3 for all Brewers (i.e. decreasing, or slowly increasing,
7 response as temperature increases for TR1, fast increasing response for TR2, and again decreasing, or
8 slowly increasing, response for TR3), with the results of Ylianttila and Schreder (2005) leads to the
9 conclusion that part of the observed changes is due to the effect of temperature on the transmittance of the
10 diffuser, ~~while the rest is mainly due to changes in the response of the PMT and the transmittance of the~~
11 ~~internal optical components.~~ However, the slope of the linear fit in TR1 and TR3 is in most cases different
12 than what would be expected according to their results indicating that part of the dependence also is due
13 to the effect of temperature on the PMT and other internal optical and mechanical components of the
14 instrument.

15 To investigate the validity of this assumption, spectral irradiance measurements were performed at
16 different temperatures using an external lamp through the slant quartz window, and the internal standard
17 lamp of the Brewer. The results were then compared with those from the measurements through the
18 diffuser. These measurements were performed by B005, B086 and B185 using slightly different setups.
19 For all the three Brewers it was found that, while for the measurements through the diffuser the response
20 changes differently in TR1, TR2, and TR3, for the measurements of the external lamp through the
21 window and the ~~standard lamps~~ the response changes with the same rate in the entire range of recorded
22 temperatures (Berjon and Redondas, 2017). The results for B005 are presented in Fig. 5.

23 This In Fig. 5a, the linear fits of the results are also presented. In Fig. 5b the slopes of the least square
24 linear fits and the corresponding 1 σ uncertainty in their determination are presented, as well as the second

1 degree polynomials which describe the dependence from wavelength in each case. These results confirms
2 that the different patterns found between the three TRs are mainly due to the change in the transmissivity
3 of the Teflon diffuser. For the measurements through the window it was found that the change in the
4 response/°C is wavelength dependent for both the single and the double monochromator Brewers,
5 indicating that the dependence of wavelength might not be introduced solely by the NiSO₄ filter used only
6 only in the single monochromator Brewers, as suggested by Weatherhead et al. (2001) and Garane et al.
7 (2006). Some possible explanations for the different results for the sl and the measurements through the
8 window are the following: (a) large temperature gradients exist inside the instrument when the sl is on, (b)
9 the electronic circuits of the sl may be affected by temperature and (c) the transmittance of the quartz
10 window may be affected by temperature. However, further investigation is out of the scope of the present
11 study. In order to clarify whether the changes of temperature may also affect the transmittance of the
12 quartz dome, spectral irradiance measurements with and without the dome were performed by B086 and
13 the mean spectral transmittance of the dome was derived for different temperatures. It was found that for
14 temperatures ranging between ~15 and 45 °C the dome blocks ~ 6% of the incoming radiation,
15 independently of temperature or wavelength.

16 Ylianttila and Schreder (2005) measured the transmissivity of a number of radiometric instruments,
17 none of which was a Brewer, and found that the effect of temperature on the transmissivity of the Teflon
18 diffusers mainly depends on their thickness and the wavelength of the incident irradiance. For the cases
19 they studied, they found that near 19 °C the temperature transmissivity changes range between ~ 1 and
20 3% which is in good agreement with our results. The width of TR2 also seems to differ by a few °C
21 between the different instruments used in their study. The differences between the changes of response
22 and the width of TR2 (even when the same characterization methodology was used) for the Brewers used
23 in this study denote that the individual characteristics of each diffuser may play an important role on its
24 correspondence to the changes of temperature. However, part of these differences is also related to the
25 uncertainties in the characterization procedure as explained in the following.

3.3. Uncertainties in the characterization and the correction

Ideally, the characterization should be performed separately for the effect of temperature on the transmittance of the Teflon diffuser, the transmittance of the internal optical and mechanical components and the response of the PMT. However this is not possible due to insufficient information to partition the effect among the ~~three-different~~ components, as well as due to lack of systematic recording of temperature at each component. A parameterization including the PMT and the ambient (environmental) temperature might also describe more accurately (than using only the PMT temperature) the effect of temperature since this way the possible differences between the temperature of the PMT and the diffuser would be partially taken into account. However, this would make the characterization very complicated. Furthermore, the environmental temperature out on the sun, where the Brewers are routinely operating, is different than the temperature provided by the meteorological stations which is measured in the shadow and the former is not usually recorded. Therefore, the characterization and correction is performed for the overall response to temperature using the temperature that is recorded by the thermistor attached to the PMT for each single spectral scan. The assumption that this temperature is representative for all parts of the instrument introduces some uncertainties, which are difficult to quantify.

3.3.1. Temperature gradients inside the instrument

During the characterization procedure, the 200 and 1000 Watt lamps do not warm the diffuser, and as long as the warming or cooling of the Brewer is slow ~~there are no differences between the~~ temperature ~~gradients inside the instrument~~ of the diffuser and the PMT can be considered negligible. However, during the regular operation of the Brewer, larger differences may exist. For the investigation of the differences between the temperature of the diffuser and the temperature of the PMT during the regular operation of B185, a suitable-suitably designed infrared sensor was installed inside ~~the Brewer~~ B185 to record the temperature of the lower surface of the diffuser for about a month during which the instrument was operating regularly outside, during which and the ambient temperature was ranging between ~ -2 and 27 °C. Analysis of the results revealed that when the internal heater is off, the difference is generally smaller

than 4 °C showing that even large differences between the environmental and the internal temperature, which are not unusual for Brewers (Weatherhead et al., 2001), do not imply correspondingly large differences between the temperatures of the PMT and the diffuser. However, when the heater is on (below 20 °C), temperature gradients appear in the instrument, which become more important as the temperature decreases. Under these conditions, the temperature of the diffuser is much lower than the temperature of the PMT, and for the lowest recorded internal temperatures (15 – 16 °C) differences of up to 10 °C can be encountered. For instruments for which the heater is turned on at 10 °C, the gradients are expected to be important at lower temperatures. Based on the results of Ylianttila and Schreder (2005) and the results presented in Fig 3 we estimate that the errors in the correction of measurements due to the difference between the recorded and the actual temperature of the diffuser when the heater is on are, in all the studied cases, smaller than 2%.

4.3.1.3.3.2. Hysteresis of the PMT

The hysteresis is not solely related to the temperature gradients inside the instrument when the heater is on. The interior of the PMT is a vacuum and heat conducts through it very slowly. Thus, the PMT reaches the temperature level of the environment later than other parts of the instrument and it is questionable whether the recordings of the thermistor which is attached to the PMT housing represents its actual temperature or the temperature of the housing. Hysteresis loops that have been also observed when measurements of the standard lamp were analyzed with respect to temperature (for B005, B086 and B185), as well as analysis of the characterization results for high temperatures (for which the heater is turned off) confirm this assumption. Though, the hysteresis due to the delay in the response of the PMT is estimated to have a minor impact on the overall behavior of the instrument compared to the impact of the differences between the temperature of the diffuser and the PMT.

3.3.3. Effect of temperature on the determination of the spectral response

The determination of the spectral response of the Brewers is usually performed in the laboratory using 1000 Watt lamps. As shown in Fig 2, the lamps warm the air in the calibration room, which leads to a gradual increase of the instrument's internal temperature. Depending on the instrument and the measurement settings determined by the operator, each scan of the lamp's spectrum may last from a few (~ 3 – 5 mins) to several (~20-30 mins). Thus, according to the results presented in Fig. 2, the temperature of the instrument changes during each spectral scan and at the end of the scan it may differ by a few °C. In the case of Thessaloniki the calibration room is small (a few m²) and the lamp warms the air in the room fast. Performing the calibration in a bigger room and/or improving the ventilation would lead to slower changes of the temperature. Obviously, the calibration factor should be derived for a standard temperature, or alternatively all measurements should be interpolated to the temperature of the calibration. For this purpose, the temperature which is recorded at the beginning of each scan of the lamp can be used. Based on the results presented in Figs 2 and 3 we estimate that the uncertainty in the determination of the calibration factors due to the changes of temperature during the calibration procedure will be less than ~0.5%, given that in most cases the calibration is performed at temperatures near 25 °C or higher, and the change of temperature during each spectral scan is less than ~5 °C.

~~4.3.2.~~3.3.4. Heating and cooling rate during characterization procedure

~~Measurements with B185 indicate that the temperature gradients inside the instrument become important when the heater is on and the recorded temperatures are below ~16–18°C. For instruments for which the heater is turned on at ~10°C, the gradients become important at lower temperatures. Based on the results of Ylianttila and Schreder (2005) and the results presented in Fig. 3 we estimate that the errors in the correction of measurements due to the difference between the recorded and the actual temperature of the diffuser when the heater is on are, in all the studied cases, smaller than 2%.~~

~~The uncertainties in the characterization procedure and the determination of the correction factors also induce errors in the correction of measurements, which however are estimated to be smaller than~~

~~these due to the temperature gradients inside the instruments during their regular operation.~~ If the rate of heating or cooling during the characterization procedure is not slow enough, ~~small~~ non-negligible temperature gradients may appear inside the instruments. Thus slightly different heating or cooling rates during the characterization procedure may lead to the calculation of slightly different correction factors. This may explain the differences between the two sets of measurements with B185 as well as the large spread in the measurements of B030 and B078 ~~and the correspondingly large uncertainty in the characterization results presented~~ shown in Fig. 3.

~~4.3.3.~~ 3.3.5. Photon noise

~~4.3.4.~~ —

When the signal of the lamp is low, the uncertainty in the measurements, and consequently in the characterization results, due to the photon noise may be also important (e.g. Grajnar et al., 2008). In these cases, increase of the exposure time of the PMT may improve the results. For example, the measurements for the characterization of B005 were initially performed with an exposure time of ~ 0.45 sec (the results are not presented in this study) and then were repeated with an exposure time of ~4.5 sec (results presented in Figures 3 and 4). Although the number of data points was similar in the two cases, the standard deviation in the correction factors was ~10 times larger when the exposure time was smaller. These uncertainties are generally more important at lower wavelengths where the signal of the lamp is weaker.

3.3.6. Effect of temperature on the wavelength stability

One more possible factor of uncertainty in the characterization procedure is the apparent responsivity change due to the effect of temperature on the wavelength stability of the instrument. Temperature changes lead to change of the instrument's spectral characteristics (Gröbner et al., 1998). To compensate for this effect the 297 (or 302) nm line of the internal Hg lamp is scanned when the temperature changes by ~1-2 °C and the zero position of the micrometer is adjusted properly (Grajnar et al., 2008). However,

1 the correction based on the results for 297 or 302 nm does not ensure that there are no wavelength shifts
2 at larger wavelengths. Spectra of the global solar irradiance measured by B005 and B086 were analyzed
3 using the SHICrvm algorithm (Slaper et al., 1995) and no significant dependence of the wavelength shift
4 from temperature was found. However, even if we assume a small shift in wavelength (i.e. of 0.01 nm)
5 during the characterization procedure, this would induce an important apparent responsivity change (of
6 the order of 1%) only for the single monochromator Brewers near 325 nm where the spectral response of
7 the instrument changes fast.

8 3.3.7. Number of spectra during characterization

9 The low number of measurements also increases the uncertainty in the characterization results, especially
10 when the recorded signal and the exposure time of the PMT are also low. ~~Thus, the standard deviation in~~
11 ~~the determination of the correction factors is not indicative for their quality, especially if the number of~~
12 ~~measurements is small.~~ The finite, usually low number of measurements in the TR1 and TR2 ~~also~~ induce
13 uncertainties in the determination of the TR limits and the correction factors. Thus, for each instrument,
14 slightly different TR1 - TR2 and TR2 - TR3 limits may be found when the characterization is repeated.
15 Analysis of the characterization results for four different sets of measurements (performed in different
16 days of 2005) with B086 resulted in TR2 - TR3 limits ranging between 24 and 28 °C. The same analysis
17 for B005 resulted in smaller differences (22 – 24 °C). Separate analysis of the results for the warming and
18 the cooling of B185, for the second set of measurements, also lead to different TR2 - TR3 limits, at ~30
19 °C and ~23 °C respectively. We estimate that the uncertainties in the correction factors due to these
20 differences cannot exceed $\pm 0.5\%$.

21 4.4.3.4. Evaluation of the derived correction factors

22 For the evaluation of the results presented in section 3.1, global UV spectra that were measured nearly
23 simultaneously by the two Brewer spectrophotometers operating at Thessaloniki (B005 and B086) and by
24 those operating at Sodankylä (B037 and B214) were compared to each other. For Thessaloniki,

measurements for 15 years (2001 - 201~~45~~) were used in the comparison while for Sodankylä measurements were available only for a period of six months (April – October 2016). More specifically, the 300 – 325 nm integrals of spectra measured within 1 minute were compared for each pair of collocated instruments, before and after applying the temperature correction. Since changes in temperature affect the measurements of each instrument differently, it is expected that the ratio of the uncorrected for the effect of temperature data between two instruments will be temperature dependent, and that the greatest part of this dependence would be eliminated when temperature corrected data are used instead. These ratios normalized to the ~~average for the entire temperature range~~mean ratio at 25°C are shown in ~~Fig.~~Fig. 6 for Thessaloniki and Sodankylä Brewers as a function of temperature recorded, respectively, by B086 and B037. The error bars represent the 1 σ standard deviation of the mean for each 10°C bin.

According to Fig. 6a, the temperature correction of the data of B005 and B086 almost eliminates the otherwise strong temperature dependence of their ratio. Similar results are achieved for the two Brewers operating in Sodankylä. Despite the lower temperatures in Sodankylä which may result in large temperature gradients inside each instrument when the heaters are turned on, the results verify that the applied correction is towards the right direction, even for ambient temperatures of about -10°C .

Temperature correction factors were determined for B005 and B086 operating in Thessaloniki twice, in 2005 (Garane et al., 2006) and 2015. The differences in the derived temperature correction factors are smaller than their ~~$\pm 1\sigma$~~ $\pm 1\sigma$ uncertainty suggesting that these correction factors are valid for the entire period (2001 – 2015). This has been also confirmed from the comparison of quasi-simultaneous measurements of the two instruments for this period. In contrast, the comparison of measurements for the period 1993 – 2000 revealed that the correction factors cannot remove effectively the dependence effects for this period. This can be attributed to the replacement of the PMT of B086 in 2000, which has different temperature response compared to the old PMT. Replacement of other electronic parts of B005 and B086 was not found to induce detectable changes in their behavior regarding the effects of temperature. The above

1 indicate that the temperature dependence does not change significantly with time as long as the
2 components of the instrument that are mainly affected by changes in temperature (~~i.e. the Teflon diffuser~~
3 ~~and the PMT~~) remain the same.

4 **4. Conclusions and discussion**

5 The sensitivity of the Brewer spectrophotometers in spectral irradiance measurements shows a marked
6 dependence to temperature variations. Thus, the use of uncorrected spectra for the study of the diurnal,
7 seasonal and annual changes of UV irradiance would lead to inaccurate results due to the corresponding
8 cycles of temperature. Although improper correction of the spectra for the effects of temperature would
9 not possibly have an important effect on the study of the long term changes of the UV irradiance at low
10 and mid-latitudes, it may be more important for higher latitudes where the annual mean temperature is
11 changing, and is projected to keep changing fast in the following decades (IPCC, 2007). The Accurate
12 correction of the spectra for the effects of temperature would improve the agreement between the
13 measurements from different Brewers and lead to a more reliable product which in turn would be suitable
14 for climatological studies and the validation of satellite products and model simulations.

15 The % difference of the 315nm response from its value at 25°C due to the effect of temperature is
16 presented in Fig 7 (left column). The presented results are for all the spectra measured in 2016 and for all
17 the eight Brewers used in this study. The corresponding temperatures recorded at the PMT are presented
18 in the right column of the same figure. The differences from the response at 25°C have been calculated
19 using the results of Sect. 3.1.

20 Depending on the site and the instrument, the response may differ by up to 6% (e.g. in the case of
21 B005) in a year. These differences seem to be smaller (occasionally of the order of 1.5% in a day) for
22 instruments which operate at low temperatures and the threshold of the heater is 20°C (e.g. B185 and
23 B214). However, as explained earlier, the correction of the measurements from these instruments is more
24 uncertain due to the large temperature gradients when the heater is on. According to the results presented

1 in Fig 7, there are upper and/or lower limits in the changes of the response for most Brewers. These limits
2 correspond to the turning points (limits between TR1 and TR2 and between TR2 and TR3) of the lines
3 presented in Fig. 3 and are evident because for all studied cases the temperature ranges between a lower
4 (between 0 and 20 °C) and an upper (between 30 and 50 °C) limit.

5 ~~The sensitivity of the Brewer spectrophotometers in spectral irradiance measurements shows a~~
6 ~~marked dependence to temperature variations. The response of each instrument is generally different,~~
7 ~~even for the same range of temperature. This study has shown that for internal temperatures ranging~~
8 ~~between ~10 and 50°C the sensitivity of some instruments may change by up to 5%.~~ The temperature
9 response of Brewers, either these are single or double monochromators, is wavelength dependent and
10 instrument specific. The ~~two~~ main components of the Brewer spectrophotometers that determine their
11 behavior relative to temperature variations are the PMT ~~and,~~ the diffuser, ~~although other components,~~
12 ~~such as and possibly~~ the UG11-NiSO₄ filter in the single monochromator Brewers, ~~can also be affected.~~

13 For irradiance measurements through the Teflon diffuser (global irradiance) the response is not
14 unique for the entire range of operating temperatures, mainly because of the steep increase (decrease) in
15 the transmissivity of the diffuser as the temperature increases (decreases) from ~12 (22) to 22 (12) °C. It
16 is suggested that different correction factors should be used for three different temperature ranges (TR1:
17 below ~12 °C, TR2: ~12 – 22 °C, TR3: above ~22 °C). The temperature dependence is very similar in
18 TR1 and TR3, thus applying the same correction factors for these ranges does not introduce large
19 uncertainties.

20 Characterization for the effects of temperature using the 50 Watt lamps, which are operationally used
21 to monitor the stability of the Brewer spectrophotometers, may lead to wrong correction factors since
22 these lamps are positioned very close to the diffuser, increase its temperature and alter its transmissivity.
23 The 1000 Watt lamps, regularly used for the absolute irradiance calibration at distances longer than 50
24 cm, do not heat the diffuser and lead to more reliable results when they are used for the temperature

1 characterization. The setup with 200 Watt lamps, which is used at several stations for monitoring the
2 instruments' stability, is also suitable for temperature characterization because the distance of the lamp
3 from the diffuser is adequately long to prevent direct heating.

4 The proposed methodology which is described in detail in the supplement was evaluated using
5 spectra from the Brewer spectrophotometers operating in Thessaloniki and Sodankylä and was found to
6 remove the greatest part of the temperature dependence from the irradiance measurements. The correction
7 of the spectra using the specific methodology is more accurate compared to the correction based on the
8 methodologies described in previous studies (Garane et al., 2006; Lakkala et al., 2008; Siani et al., 2003;
9 Weatherhead et al., 2001) since the effect of temperature on the transmissivity of the diffuser is also taken
10 into account. The correction factors for each Brewer depend on its individual constructional
11 characteristics, thus it is not possible to apply generic correction for all Brewer spectrophotometers and
12 characterization of each individual instrument is necessary. Repeating the characterization procedure
13 frequently was not found necessary as long as the main components of the instrument which are affected
14 by temperature variations (~~mainly the Teflon diffuser and the PMT~~) are not replaced.

15 The uncertainties in the calculated correction factors are small as long as the warming and cooling of
16 the instrument is slow enough to prevent the development of large temperature gradients inside the
17 instrument during the characterization procedure. Increasing the number of measured spectra and/or the
18 exposure time of the PMT, especially at temperatures between ~10 and 25 °C, may lead to smaller
19 uncertainties in the derived correction factors. Uncertainties in the correction of global irradiance spectra
20 arise mainly from the use of the temperature recorded at the PMT to correct the measurements. Large
21 temperature gradients inside the instrument when the heater is turned on, may occasionally lead to large
22 differences, of the order of 10 °C, between the actual temperatures of the PMT and the diffuser. For
23 particular instruments, these differences may subsequently lead to errors of up to 2% in the correction of
24 spectra recorded with the heater on. The uncertainties due to the characterization procedure and the

1 methodology to derive the correction factors are estimated to be generally smaller than 0.5% and more
2 important for temperatures below ~25 °C.

3
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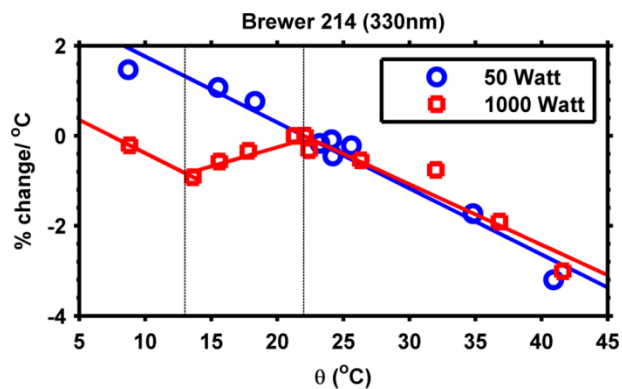


Figure 1. Changes in the response of B214 at 330 nm, relative to the response at 25 °C for the same wavelength, as a result of changes in temperature, derived using 50 and 1000 Watt tungsten – halogen lamps.

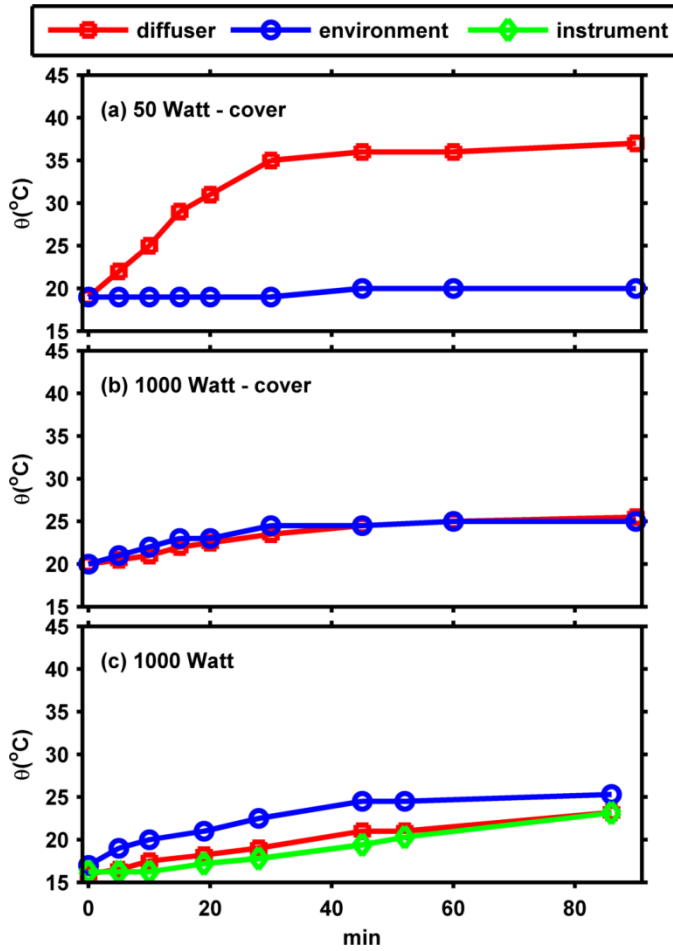


Figure 2. Change of the temperature of the diffuser of B005 (a) when a 50 Watt lamp is placed at a vertical distance of 5 cm above the diffuser and only the cover is used, (b) when a 1000 Watt lamp is placed at a vertical distance of 50 cm above the diffuser and only the cover is used, (c) when a 1000 Watt lamp is placed at a vertical distance of 50 cm above the diffuser and the instrument is operating normally (the instrument is inside the cover).

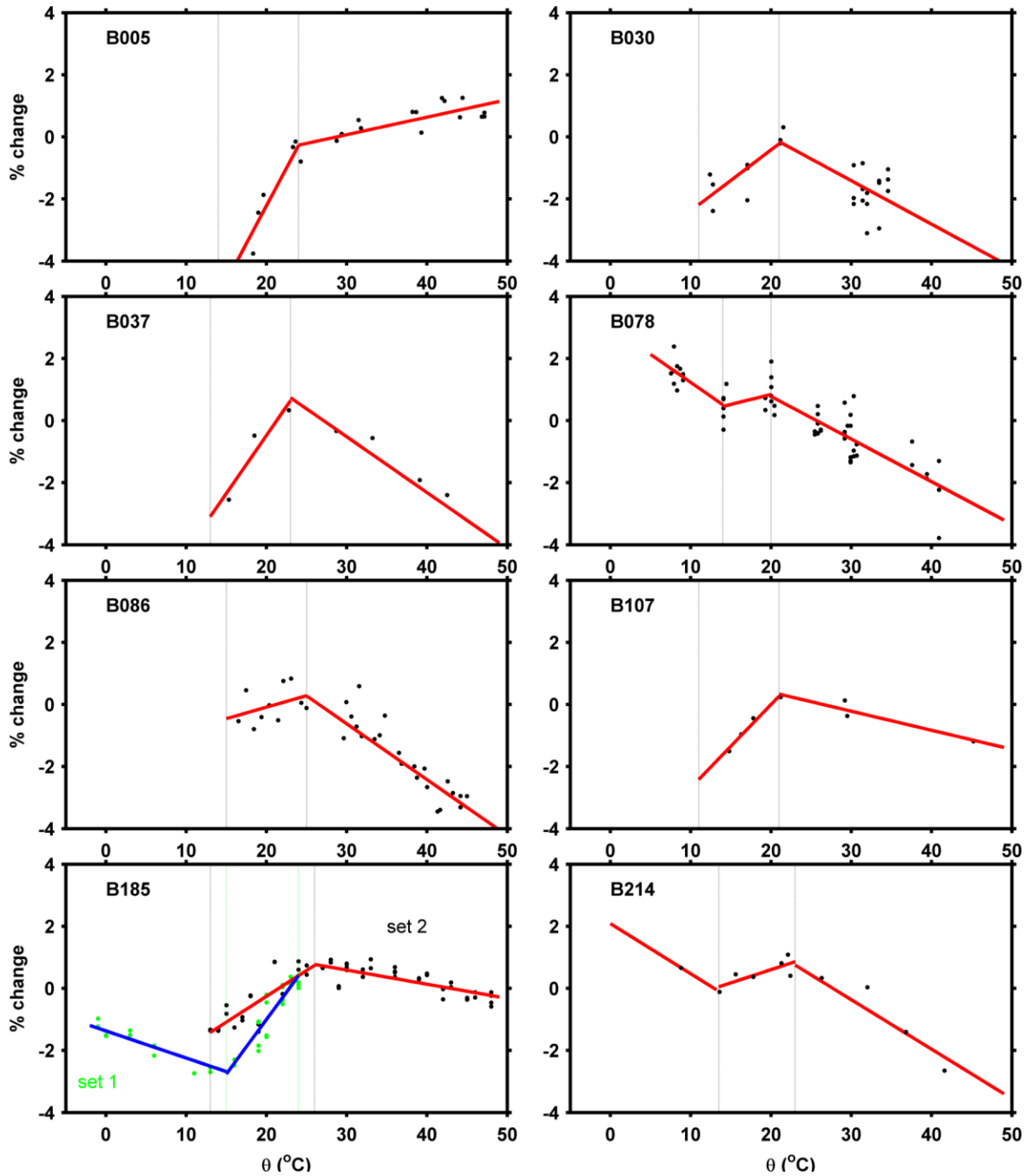


Figure 3. Change (in %) in irradiance at 315 nm with respect to the instrument's internal temperature for eight Brewer spectrophotometers. The estimated limits that separate the three TRs for each instrument are represented by the two dotted lines, while the linear fits that describe the change in each instrument's response are represented by the red lines. For B185 the two sets of measurements are represented by different colors (green and black) as well as the corresponding linear fits (blue and red).

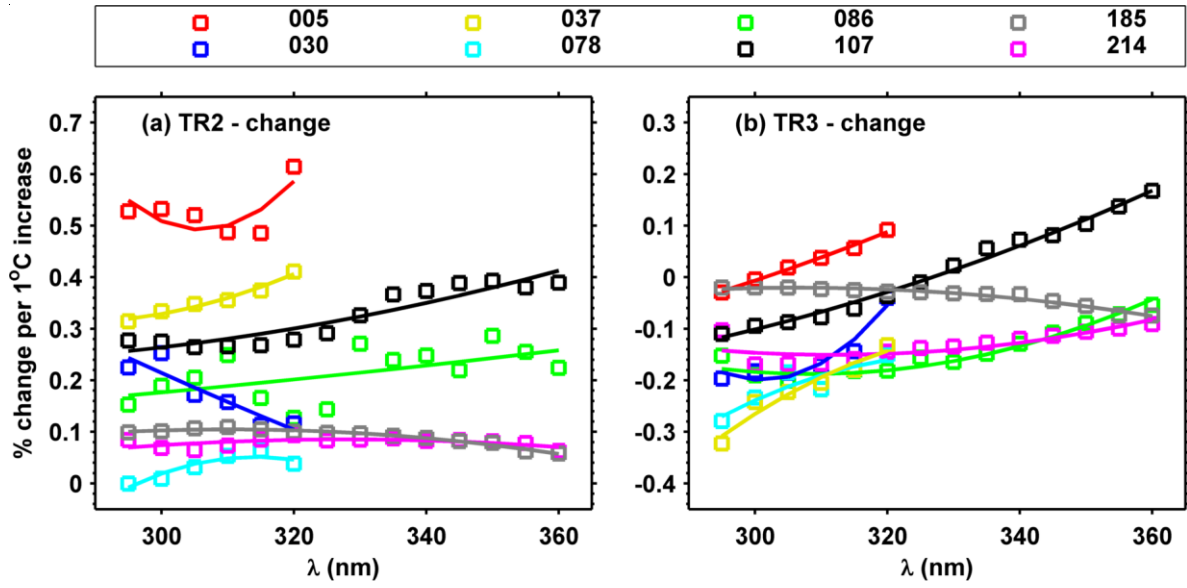


Figure 4. Change (in %) of irradiance ~~at 315 nm~~ for 1 °C increase in temperature as a function of wavelength for (a) TR2 and (b) TR3 for the eight Brewers.

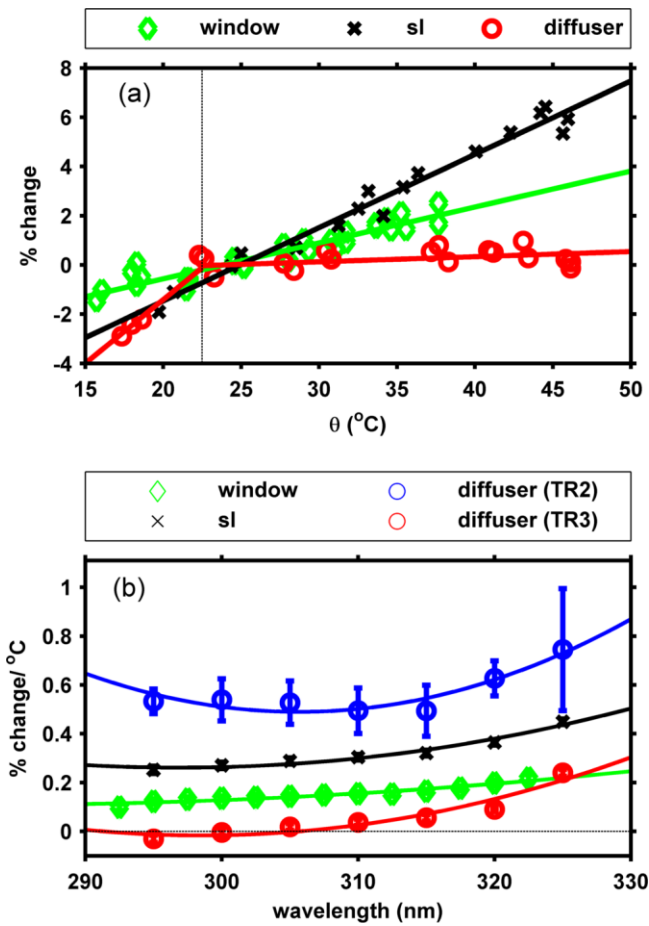


Figure 5. (a) Change in the response of B005 as a function of temperature for the sl and measurements through the window and the diffuser, relative to the response at 25 °C and (b) the dependence of the derived slopes from wavelength.

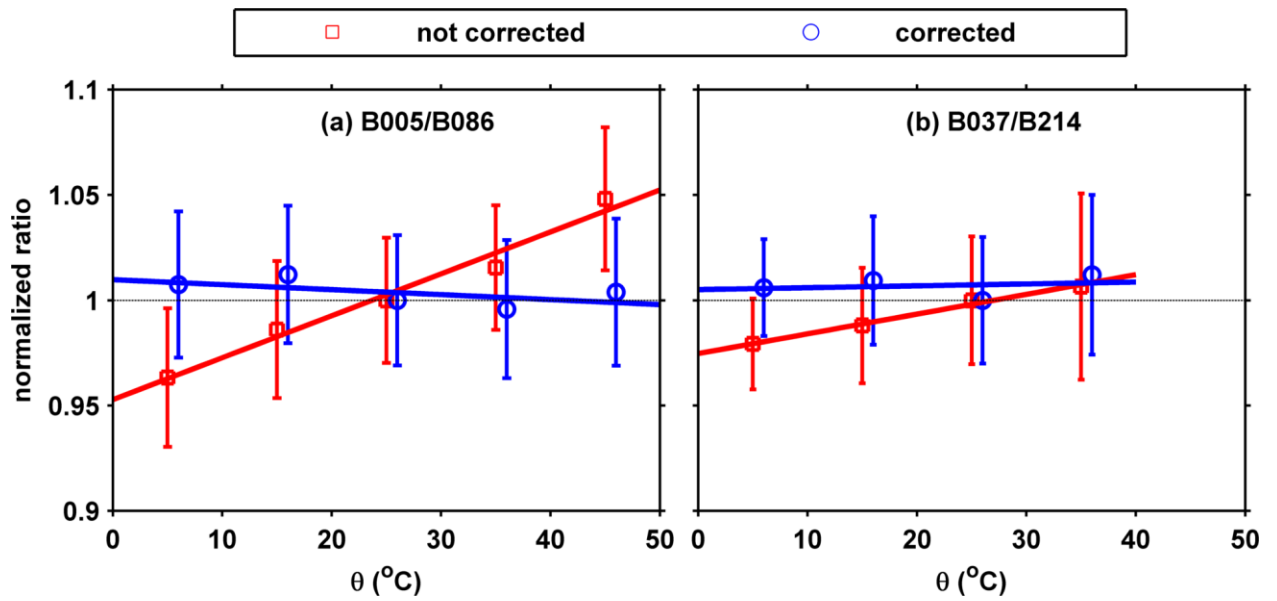
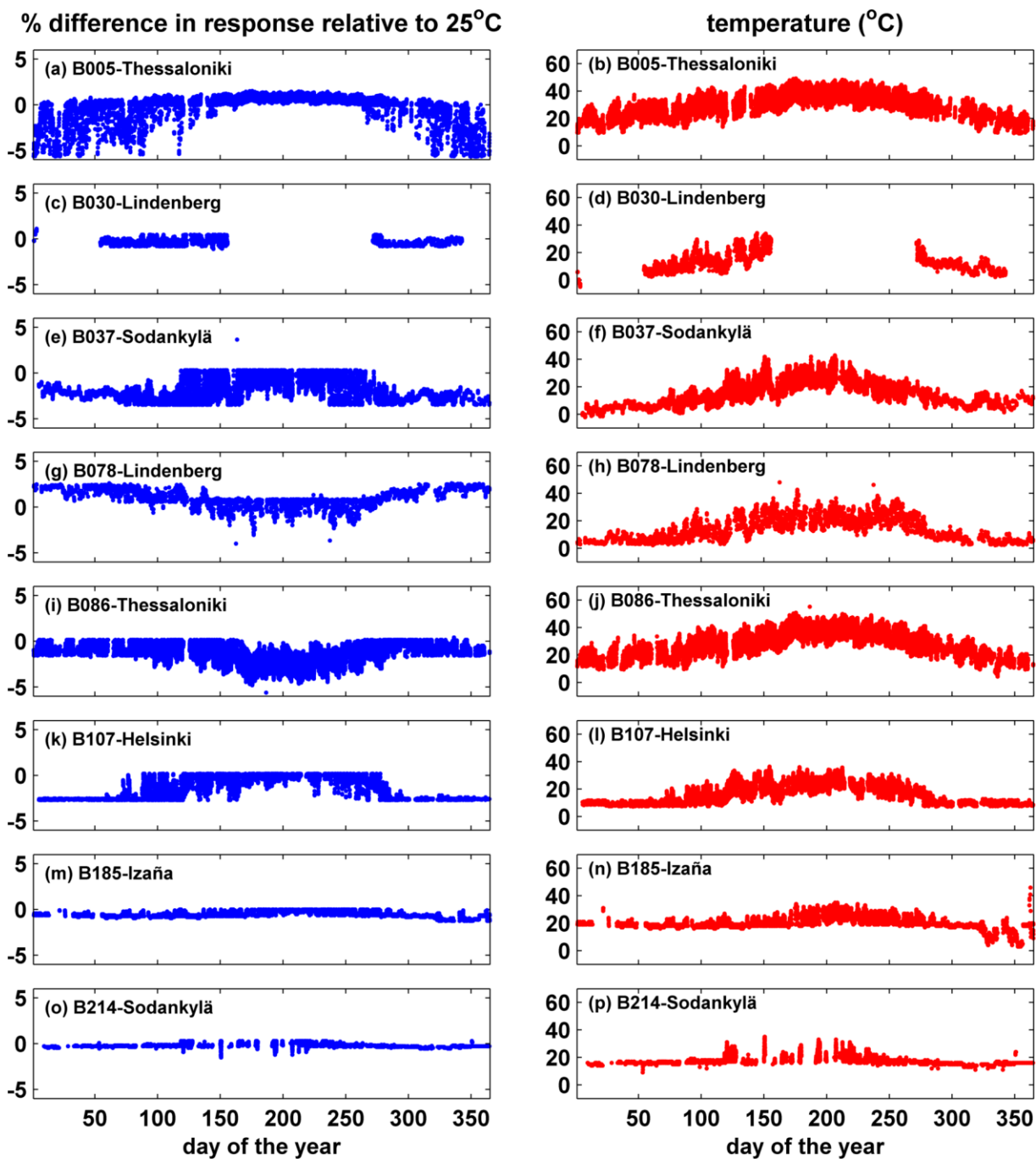


Figure 65. Normalized ratio of the 300 – 325 nm irradiance integrals derived for each pair of Brewers as a function of temperature before and after applying a temperature correction for (a) B005 and B086 in Thessaloniki and (b) B037 and B214 in Sodankylä. The ratios have been normalized to the mean ratio at 25 °C. The error bars represent the 1σ standard deviation of the mean for each 10 °C bin.

1



2

3 **Figure 7.** Differences (%) of the 315nm response from its value at 25 °C due to the effect of temperature
 4 and the corresponding temperatures.

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Table 1. Information for each Brewer spectrophotometer and the corresponding temperature characterization procedure.

<u>Site</u>	<u>Instrument (Type)</u>	<u>Monochromator (NiSO₄ filter)</u>	<u>Characterization Method</u>	<u>Temperature range (°C)</u>
<u>Helsinki, Finland</u>	<u>B107 (MKIII)</u>	<u>Double (no)</u>	<u>Laboratory measurements using 1000 Watt lamp, FMI facilities</u>	<u>~ 15 - 30</u>
<u>Izaña, Tenerife, Spain</u>	<u>B185 (MKIII)</u>	<u>Double (no)</u>	<u>Measurements in climate chamber using 200 Watt lamp, PTB facilities</u>	<u>~ -5 - 50</u>
<u>Lindenberg, Germany</u>	<u>B030 (MKIV)</u>	<u>Single (yes)</u>	<u>Measurements in climate chamber using 200 Watt lamp, DWD facilities</u>	<u>~ 10 - 35</u>
	<u>B078 (MKIV)</u>	<u>Single (yes)</u>	<u>Watt lamp, DWD facilities</u>	<u>~ 5 - 45</u>
<u>Thessaloniki , Greece</u>	<u>B005 (MKII)</u>	<u>Single (yes)</u>	<u>Laboratory measurements using 1000 Watt lamp, LAP facilities</u>	<u>~ 15 - 50</u>
	<u>B086 (MKIII)</u>	<u>Double (no)</u>	<u>Watt lamp, LAP facilities</u>	<u>~ 15 - 45</u>
<u>Sodankylä, Finland</u>	<u>B037 (MKII)</u>	<u>Single (yes)</u>	<u>Laboratory measurements using 1000 Watt lamp, FMI facilities</u>	<u>~ 10 - 45</u>
	<u>B214 (MKIII)</u>	<u>Double (no)</u>	<u>Watt lamp, FMI facilities</u>	<u>~ 10 - 45</u>