Correction of Angular Response Error in Brewer UV Irradiance Measurements

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ABSTRACT

Ultraviolet spectral irradiance measured by spectroradiometers usually presents high deviations from the ideal angular response due to imperfections in the entrance optics. In this paper a methodology to correct the angular error in the global UV spectral measurements of a Brewer MKIII spectroradiometer under all weather conditions is presented. This methodology calculates the global correction factor as a function of three variables: the direct irradiance correction factor, the diffuse irradiance correction factor, and a factor depending on the direct-to-global irradiance ratio. This work contributes to better measuring the UV radiation by improving the parameterization of the clouds effects.

Depending mainly on wavelength, solar zenith angle, and cloud optical thickness, the angular correction obtained ranges from 2% to 9%. The accuracy of this correction is limited by the uncertainties in the measured angular response and in the ratio of direct to global radiation. The original and the corrected Brewer measurements are compared with simultaneous values of the transportable Quality Assurance of Spectral Ultraviolet Measurements in Europe through the Development of a Transportable Unit (QASUME) reference spectroradiometer. A notable decrease (about a factor higher than 2) in the relative differences between the two instruments is obtained when Brewer-corrected measurements are considered.

1. Introduction

Satellite and ground-based measurements have detected a significant decrease in the amount of total ozone during the last decades. This fact could cause an increase in the UV radiation that reaches the earth's surface. Although ground-based UV measurements are not available for a long enough period to detect long-scale trends, several studies have reported a notable increase in UV radiation at the surface in recent years. For example, Fioletov et al. (2001) found an increase of 20% in UV spectral irradiance at 300 nm at Toronto, Canada, during the 1989–96 period. This notable increase could lead to a variety of adverse effects on health and environment conditions (Diffey 1991; WMO 2003). Therefore, several international organizations have stressed the need for monitoring the UV irradiance at ground level. In addition, in order to improve our understanding of the interaction between this radiation and atmospheric attenuators such as clouds, ozone, or aerosols, the World Meteorological Organization (WMO) has remarked upon the importance of operational stations with well-calibrated, high-resolution UV spectral measurement instruments (WMO 1997).

Usually, global solar UV spectral irradiance, recorded by a Brewer spectroradiometer, presents a no-

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table deviation from the ideal angular behavior (Josefsson 1986). This deviation is due to imperfections in the entrance optics and results in the underestimation of the measured irradiances. The relative magnitude of this deviation can rise to 15% (Gröbner et al. 1996; Bais 1997). Thus, the angular response error is one of the most important sources of uncertainty in solar spectral irradiance measurements of Brewer spectroradiometers (Bernhard and Seckmeyer 1999).

While the part of the angular response error corresponding to direct radiation depends singularly on the solar zenith angle (SZA), the contribution of diffuse radiation depends on wavelength and atmospheric conditions (mainly cloudiness) (Fioletov et al. 2002). As a result, the total angular response error of a global radiation measurement depends on the wavelength, solar zenith angle, and atmospheric conditions (Bais et al. 1998).

These above-mentioned dependences of the angular response error could cause significant differences between measurements performed by instruments installed at different locations (Kimlin et al. 2003; Bais et al. 2005). Moreover, this variability may also affect the homogeneity of the measurements recorded by the same instrument under different atmospheric conditions. Therefore, it is of great importance to develop methodologies to correct this source of uncertainty.

This paper presents a method of characterizing the angular response error in global UV spectral irradiance under all weather conditions and its application to measurements taken with a Brewer MKIII spectroradiometer located at the El Arenosillo Atmospheric Sounding Station (ESAt, near Mazagón, Spain). In recent years, various methodologies have been developed in order to obtain the angular correction of spectroradiometers (Seckmeyer and Bernhard 1993; Bais et al. 1998; Fioletov et al. 2002). All of these methods use three terms to determine the global irradiance correction factor: the direct and diffuse irradiance correction factors and the direct-to-global irradiance ratio. In this work, the direct irradiance correction factor is calculated by measuring the angular response of the spectroradiometer in the calibration laboratory using a quartz–halogen National Institute of Standards and Technology (NIST)-traceable standard lamp. In addition, theoretical expressions are used to calculate the diffuse irradiance correction factor assuming an instrument's cosine deviation is independent of the azimuth angle and an isotropic diffuse solar radiation field. Finally, the direct-to-global irradiance ratio is estimated by means of the radiative transfer model, the UVSpec/libRadtran (Mayer and Kylling 2005).

The original contribution of this paper is the characterization of the cosine correction for cloudy conditions. Most of previous works in the literature used radiative transfer models for characterizing the cloudy conditions when the only information available is global UV irradiance (Fioletov et al. 2002; Bernhard et al. 2003). In this paper, the proposed algorithm obtains the cloud information from a semiempirical method. In brief, cloud transmittance is calculated for each weather condition as the ratio between the Brewer measurements and cloud-free estimations by an empirical algorithm. In a second step, the global irradiance correction is calculated using a lookup table (LUT) obtained by means of the UVSpec model. Another interesting contribution from this paper is the interpretation of the results, when the uncorrected and the corrected data of the Brewer instrument are compared to a well-established reference instrument.

The paper is structured as follows: Section 2 presents the main characteristics of the Brewer MKIII spectroradiometer used in this work. Section 3 describes the method for correcting the angular response error. In section 4 the correction factor of global UV spectral irradiance is calculated. Moreover, the intercomparison between the Brewer spectroradiometer and the transportable Quality Assurance of Spectral Ultraviolet Measurements in Europe through the Development of a Transportable Unit (QASUME) reference spectroradiometer is analyzed in order to evaluate the reliability of the correction method. Finally, section 5 summarizes the conclusions.

2. Instrumentation

The Brewer MKIII double-monochromator spectrophotometer No. 150 measures the global UV spectral irradiance between 290 and 363 nm with a spectral resolution full width at half maximum (FWHM) of ~0.6 nm, and a wavelength accuracy of 0.05 nm. A complete wavelength scan takes 4.5 min. The spectrophotometer is periodically calibrated by comparison with a quartz–halogen NIST-traceable standard lamp (1000-W DXW type) with an uncertainty of 1.56% at 250 nm and 1.12% at 350 nm. This calibration transfer produces uncertainties of ±5% in the Brewer spectral irradiance measurements (Vilaplana 2004). Finally, the Brewer No. 150 is also calibrated for total-column ozone every 2 yr against a Brewer traveling standard (Brewer No. 017) from the International Ozone Services (IOS, Toronto, Canada), previously calibrated against the triad of Brewer spectrophotometers located at the Meteorological Service of Canada (international world reference of Brewer instruments). All these calibration processes guarantee the quality and accuracy of the Brewer

UV spectral measurements used in this work. Thus, standard uncertainties are limited to within ±10%.

The Brewer spectroradiometer is located at the El Arenosillo Atmospheric Sounding Station. This station belongs to the Earth Observation, Remote Sensing and Atmosphere Department, Sciences Division, National Institute of Aerospace Technology of Spain (INTA). It is located in Mazagón, Huelva, Spain (37.1°N, 6.7°W, 20 m MSL). This center participates in the Global Ozone Observing System (GO3OS) of the Global Atmosphere Watch (GAW) program of the World Meteorological Organization (WMO) as station 213. Data gathering, retrieval, and reporting procedures at these stations are standardized by the WMO quality assurance procedures. This location presents 156 cloud-free days per year (Toledano 2005), a uniform surface albedo, and suitable conditions for reliable radiometric observations. In fact, it has been chosen by the Spanish Weather Service (INM) for the periodic intercomparison campaigns of the Brewer spectrophotometers belonging to the UV radiation national network.

3. Methodology

The correction of the angular response error is mathematically described by the global correction factor (f_g). This factor is defined as the ratio between the measured global UV irradiance (E'_g) and the UV irradiance (E_g) measured by an ideal instrument. If E'_g is divided into its direct (E'_b) and diffuse (E'_d) components, then it is possible to define the global correction factor for the angular response of a spectroradiometer as

$$f_g = \frac{E'_g}{E_g} = \frac{E'_b + E'_d}{E_g}. \tag{1}$$

A global correction factor equal to one would indicate that the behavior angular of the instrument follows the ideal angular response. In addition, the correction factors for the diffuse (f_d) and direct (f_b) components can be defined as

$$f_b = \frac{E'_b}{E_b}, \quad f_d = \frac{E'_d}{E_d}, \tag{2}$$

where E_b and E_d are the direct and diffuse components of the global UV irradiance measured by an ideal instrument, respectively.

The proportions of the direct and diffuse components that compose the global UV irradiance are defined by the following expressions:

$$R = \frac{E_b}{E_g}, \quad 1 - R = \frac{E_d}{E_g}. \tag{3}$$

Finally, the definitive form of Eq. (1) can be written as (Bais et al. 1998)

$$f_g = Rf_b + (1 - R)f_d. \tag{4}$$

Therefore, in order to obtain the global correction factor for the angular response of a spectroradiometer, it is necessary to calculate f_b, f_d, and R.

a. Direct correction factor (f_b)

A radiation beam, $E_b(\theta)$, received by a radiance instrument at the incident angle θ should produce a signal proportional to $E_b(\theta = 0)\cos\theta$. However, the measured radiation usually deviates from this law, particularly at high incidence angles. Thus, the ratios $f_b(\theta)$, where

$$f_b(\theta) = \frac{E_b(\theta)}{E_b(\theta = 0)\cos\theta}, \tag{5}$$

are not equal to one for all incidence angles θ and show a dependence on the incidence angle. The ratios between the measurements of spectroradiometer at the incident angle θ and the measurement made at $\theta = 0°$ will give information about the actual angular behavior of the spectroradiometer. This angular deviation can be approximated by a function called the angular response (f). Thus, the direct correction factor can be expressed as

$$f_b(\theta) = \frac{E_b(\theta)/E_b(\theta = 0)}{\cos\theta} = \frac{f(\theta)}{\cos\theta}. \tag{6}$$

The wavelength dependencies that $f_b(\theta)$ could present are small and can be neglected for the narrow wavelength interval of the Brewer spectroradiometer (Feister et al. 1997).

To determine the direct correction factor of the Brewer instrument, a 1000-W DXW quartz–halogen lamp was placed above the quartz dome of the spectroradiometer. The lamp was fixed to a specially designed lamp holder that allows the lamp to be rotated along a circular path at small steps of incidence angle from normal incidence down to horizontal position. The experimental setup has been designed to reach a high level of accuracy in the angle positioning of the lamp.

b. Diffuse correction factor (f_d)

The correction factor of the individual values of diffuse UV radiation can be calculated from the direct correction factor by means of the following expression (Bais et al. 1998):

$$f_d = 2\int_0^{\pi/2} f_b(\theta)\sin\theta\cos\theta\, d\theta, \tag{7}$$

where θ is the zenith angle.

To apply this correction, it is necessary to assume that the instrument's angular response error is independent of the azimuth angle and that the diffuse solar radiation is isotropic. As was shown by Feister et al. (1997), the first requirement is acceptable for UV radiation. These authors concluded that the azimuth angle changes cause variations of the angular response errors within ±1% for solar zenith angles under 80°. Moreover, Bais et al. (2005) showed that the azimuth uncertainty is negligible for Brewer No. 150. According to Bais et al. (1998), the second assumption is not valid under any sky conditions and may lead to underestimation of the correction factor even under cloud-free conditions. However, it is very difficult to evaluate the deviation of that approximation for different conditions: cloudy or partly cloudy skies, atmospheres with high aerosol load, etc. Therefore, an isotropic diffuse solar radiation field is generally assumed (Blumthaler et al. 1996; Feister et al. 1997; Fioletov et al. 2002). This assumption has also been considered in this paper.

c. *Direct-to-global ratio correction (R)*

The partitioning of global radiation in direct and diffuse radiation depends on the solar zenith angle, wavelength, cloudiness, ozone, aerosol load, and other atmospheric conditions. The UVSpec/libradtran model (Mayer and Kylling 2005) has been used in order to estimate this partitioning under different atmospheric conditions.

Model calculations of spectral direct and global UV irradiances were carried out at steps of 0.5 nm for the following wavelengths: λ = 305, 324, and 350 nm. The Rayleigh atmosphere and the θ variation between 0° and 80°, with steps of 1°, were considered. The radiative transfer calculations were performed for different cloud optical thicknesses (τ) with values between 0.0 and 3.0, in steps of 0.25.

Fortunately, the ratio between the direct and global radiations shows only a slight dependence on total ozone (Zeng et al. 1994). Thus, the total ozone was considered constant with a value of 310 Dobson units (DU; mean value in ESAt El Arenosillo).

Moreover, a constant and low-surface albedo of 2% was introduced into the model. This value suitably describes the uniform surface conditions at El Arenosillo during the whole year, being surrounded by pine trees.

Finally, aerosol load was not considered in the model. This assumption could be valid for cloudy conditions since the aerosol effect is small and may be included in the cloud optical depth. In contrast, a high aerosol load with cloud-free conditions could result in a notable underestimation of the variable R by the model. However, model sensitivity studies have shown that a usual variation in aerosol optical depth of 0.2 produces a very low relative difference (less than 1%) in the total uncertainty of the correction method.

d. *Global correction factor (f_g)*

The global correction factor is a function of solar zenith angle and cloud optical thickness for each wavelength. In this paper, cloud contribution is estimated using a semiempirical method. First, the cloud transmittance is estimated by UVSpec model calculations, carried out for typical cloud optical thicknesses (τ), as

$$A^{\text{model}}(\lambda, \theta, \tau) = \frac{E_g(\lambda, \theta, \tau)}{E_g(\lambda, \theta, \tau = 0)}. \qquad (8)$$

For each cloud transmittance value, it is possible to calculate $R = E_b/E_g$, since λ, θ, and τ are known. Therefore, for each wavelength, and know pairs of values A, θ, the global correction factor was estimated by Eq. (4). Thus, an LUT of the global correction factors with θ values in columns and A values in rows was obtained for each wavelength.

On the other hand, the cloud transmittance for each Brewer measurement was obtained as

$$A^{\text{Brewer}}(\lambda, \theta) = \frac{E^{\text{Brewer}}(\lambda, \theta)}{E^{\text{Cloudless}}(\lambda, \theta)}, \qquad (9)$$

where E^{Brewer} is the global UV irradiance measured by the Brewer spectroradiometer and $E^{\text{Cloudless}}$ is the global UV irradiance estimated for cloud-free sky. This estimation was performed by using an empirical algorithm obtained by the regression analysis between Brewer cloud-free measurements and the cosine of the solar zenith angle. Neither irradiance is corrected for the angular response error. This fact produces the result that A^{Brewer} presents a slight dependence on cloud optical thicknesses and zenith angle. Thus, the relative differences between A^{Brewer} values using corrected and uncorrected irradiances (λ = 324 nm) are lower than 1% and 4% for low and high zenith angles, respectively.

Finally, using the A^{Brewer} and solar zenith angle values, the global correction factor f_g is obtained by the interpolation in the LUT for each wavelength.

4. Results

The first step in the procedure was to obtain the angular response of the Brewer spectroradiometer at ESAt laboratory using a quartz–halogen NIST-traceable standard lamp (1000-W DXW). Figure 1 shows the real and ideal angular responses and the ratio between them. It is shown that the Brewer response deviates from the ideal response, mainly for high zenith

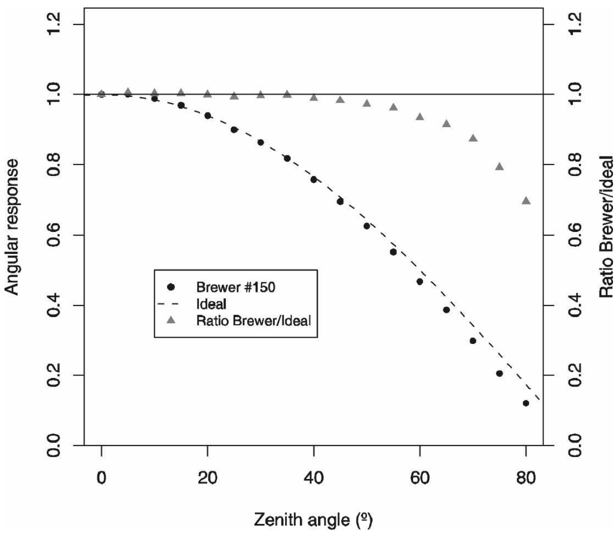

FIG. 1. Angular response of Brewer MKIII spectroradiometer.

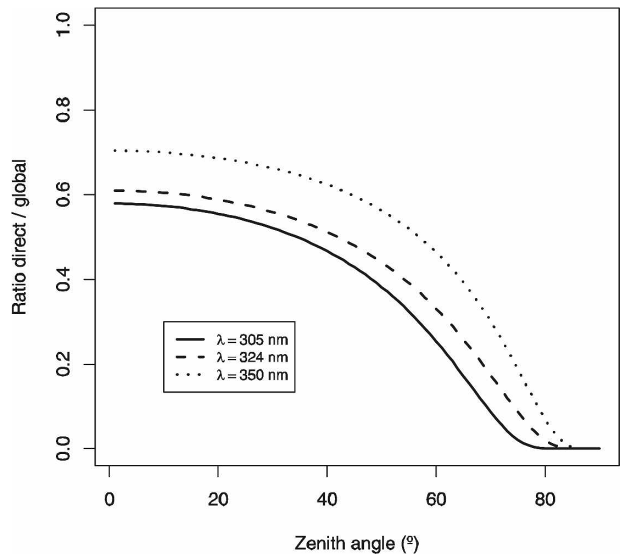

FIG. 2. Variations in the direct-to-global ratios (R) as a function of SZA (θ) and three wavelengths (λ) for cloudless cases.

angles. Thus, the angular deviations from the ideal curve are about 7%, 13%, and 30% at $\theta = 60°$, 70°, and 80°, respectively. The values are calculated as the ratio between the Brewer measurements for the incident zenith angle θ and the measurement made for $\theta = 0°$. The uncertainty of the laboratory measurements could be affected by changes in the orientation of the lamp and in the distance between the spectroradiometer and the lamp. However, these uncertainties are within ±1% and can only affect directly the correction factor by a percentage of a similar magnitude. The angular response function of the Brewer spectroradiometer can be approximated by an empirical expression as (Fioletov et al. 2002)

$$f(\theta) = (\cos\theta)^a. \qquad (10)$$

The exponent of this expression is calculated by a linear regression on a log–log plot. The resultant slope of this regression is $a = 1.126$, and the coefficient of the determination $R^2 = 0.91$. The expanded uncertainty (with coverage factor $k = 2$) of this slope is 0.022. Thus, if Eq. (10) is introduced in Eq. (2), the direct correction factor of the Brewer spectroradiometer can be defined as

$$f_b(\theta) = \frac{(\cos\theta)^a}{\cos\theta} = (\cos\theta)^{0.126}. \qquad (11)$$

To calculate the diffuse correction, the direct correction factor is introduced in Eq. (7), resulting in

$$f_d = 2\int_0^{\pi/2} (\cos\theta)^{0.126} \sin\theta \cos\theta \, d\theta. \qquad (12)$$

This integration can be solved using the variable transformation $x = \cos\theta$. Thus, Eq. (12) gives

$$f_d = -2\int_1^0 x^{1.126}\, dx = \frac{2}{1 + 1.126} = 0.94, \qquad (13)$$

with an expanded uncertainty ($k = 2$) of 0.01.

Therefore, in the absence of direct solar radiation (cloudy conditions), the Brewer number 150 underestimates by 6% the measurements of an ideal instrument for all wavelengths. This result agrees with the work of Bais et al. (2005).

If direct and diffuse irradiances are known, it is possible to determinate the angular correction of the global UV irradiance using Eq. (4). In ESAt, only the global UV irradiance is measured by the Brewer instrument. Therefore, UVSpec model calculations are needed to estimate the partitioning under different cloud conditions.

As shown in Fig. 2, the variable R depends on the wavelength. The dependence seems stronger in the UV-A region than in the UV-B region. Thus, the relative difference between the wavelengths $\lambda = 305$ and $\lambda = 324$ nm for SZA = 30° is 7.2%. In contrast, the relative difference between the wavelengths $\lambda = 324$ and 350 nm is notably higher (18.5%). For high solar zenith angles the relative differences are extremely high (higher than 70% for $\theta = 70°$). It must be noted that these high relative differences result in low absolute differences since they correspond to high solar zenith angle cases where direct irradiance is remarkably lower

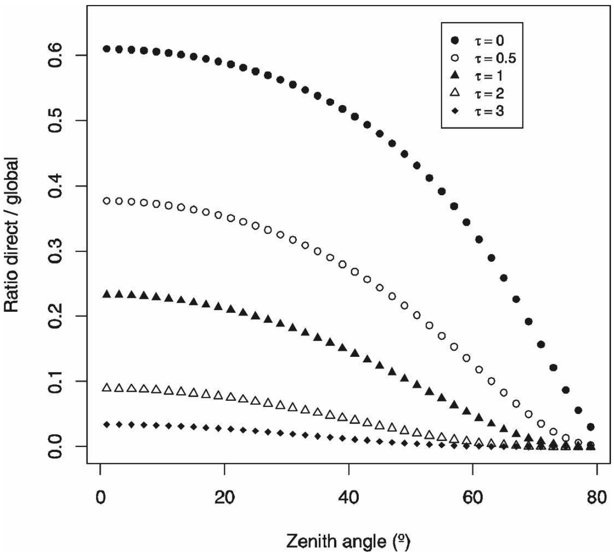

FIG. 3. Variations in the direct-to-global ratios (R) as a function of SZA (θ) and cloud optical thickness (τ) for λ = 324 nm.

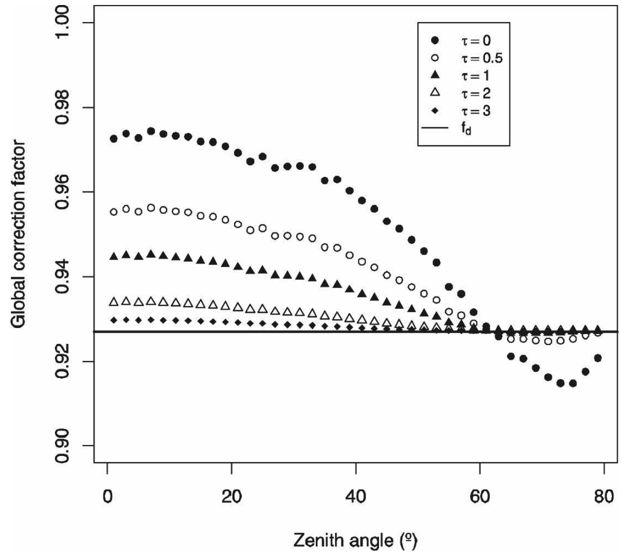

FIG. 4. Variations in the global correction factor (f_g) as a function of SZA (θ) and cloud optical thickness (τ) for λ = 324 nm.

than diffuse. All these results agree with the results obtained by Fioletov et al. (2002).

Figure 3 shows the dependencies of the ratios on the θ and τ values. It can be seen that even for in low θ and cloud-free conditions, the diffuse radiation contributes about 40% to the global UV irradiance. Figure 3 shows that the ratio decreases quickly with increasing θ and increasing cloud optical thickness. For larger θ and cloud optical thicknesses, the ratio tends to zero since the diffuse component dominates. If τ values higher than 3 are used in the UVSpec model, results show that the direct component of the global UV radiation is practically zero at the surface. Thus, in this paper the direct-to-global ratio is considered null for the cases with τ values higher than 3 since for these cases the global UV radiation is only composed of diffuse radiation.

When the variables f_b, f_d, and R are estimated, the global correction factor can be calculated by Eq. (4). Figure 4 shows the f_g variation as function of θ and τ values for λ = 324 nm. The angular correction of the Brewer spectroradiometers varies from 2% to 9%, and it is determined by θ and τ values corresponding to each radiative measurement. It can be seen that f_g values approach the value of the diffuse correction for high τ values. This fact agrees with the nearly null direct-to-global ratio for these cases, resulting in $f_g = f_d$.

Figure 5 shows the f_g variation as function of θ for $\tau = 0$ and three different wavelengths (305, 324, and 350 nm). It can be seen that the three curves show a similar pattern. The absolute differences between the f_g factors for the three wavelengths are larger for high solar zenith angles. These dependences on the solar zenith angle can only be due to the absolute differences in the variable R and the absolute differences between the f_b and f_d factors [Eq. (4)]. On the one hand, the variable R has very low values for high solar zenith angle (Fig. 2); thus, the absolute differences in the variable R are very low for high solar zenith angles. In contrast, the absolute differences between the f_b and f_d factors are notably high for those angles. Therefore, this last fact is responsible for the differences between the f_g factors for the high solar zenith angles shown in Fig. 5.

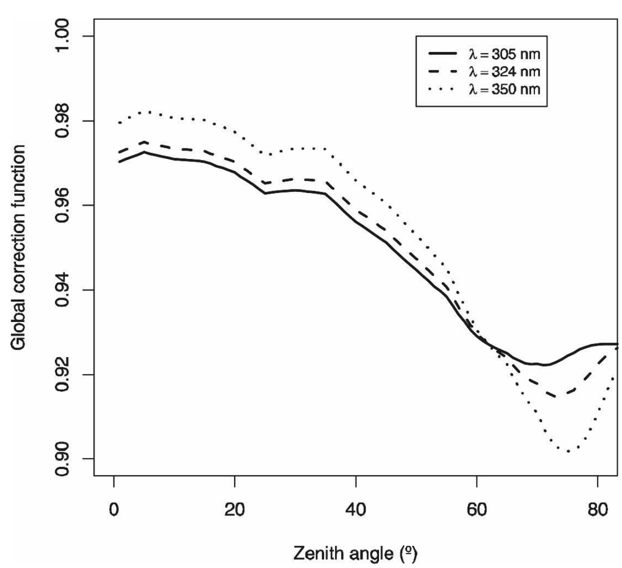

FIG. 5. Variations in the global correction factor (f_g) as a function of SZA (θ) for τ = 0 and three wavelengths (305, 324, and 350 nm).

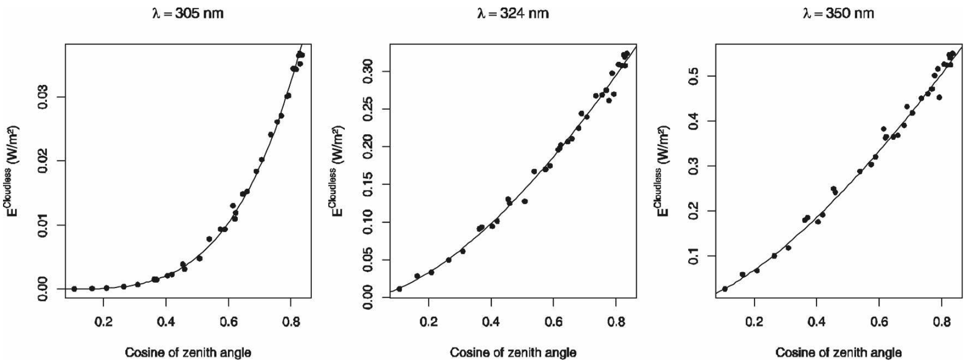

FIG. 6. Evolution of UV spectral irradiance, for cloudless cases, with respect to cosine of SZA (θ) for λ = (left) 305, (middle) 324, and (right) 350 nm.

For each group of values θ, τ, and λ, it is possible to estimate the A parameter [Eq. (8)] by the UVSpec model and the f_g factor by Eq. (4). Thus, one LUT with 91 columns (θ values) and 13 rows (A values) is obtained for each wavelength.

To demonstrate the effectiveness of the methodology, we compare measurements from the Brewer spectroradiometer before and after applying the correction with simultaneous measurements of the transportable reference spectroradiometer used for the QASUME project. The measurements were taken as part of the European Brewer Spectroradiometer Intercomparison within the framework of the Global Atmosphere Watch project. This campaign took place at El Arenosillo in September 2005.

The transportable QASUME reference spectroradiometer is considered to be the European irradiance reference. The QASUME scale represents the average scale in use at 25 independent European laboratories (Gröbner et al. 2006). The expanded uncertainty (k = 2) of the transportable QASUME reference spectroradiometer was estimated at less than 5% for the wavelength range 310–400 nm and for an SZA equal to or lower than 75°. The contribution of the angular response to this uncertainty is 0.4% at 300 nm and 0.8% at 400 nm (Gröbner et al. 2005). Moreover, the absolute scale carried by the QASUME instrument is traceable to the primary irradiance standard of the Physikalisch-Technische Bundesanstalt (PTB) located at Braunschweig, Germany (Gröbner and Sperfeld 2005).

First, the semiempirical cloud transmittance was calculated by means of Eq. (9). For that, it is necessary to approximate the Brewer cloud-free measurements to θ values by an empirical expression for each wavelength. Figure 6 shows the relation of the Brewer cloud-free values with the cosine of the solar zenith angle for wavelengths of 305, 324, and 350 nm. A clear dependence can be seen between the two variables. By performing a linear regression on a log–log plot, the following expressions were obtained:

$$E^{\text{Cloudless}}(\lambda = 305, \theta) = (0.078 \pm 0.004) \cos\theta^{(3.95 \pm 0.09)}, \tag{14}$$

$$E^{\text{Cloudless}}(\lambda = 324, \theta) = (0.421 \pm 0.014) \cos\theta^{(1.58 \pm 0.04)}, \tag{15}$$

and

$$E^{\text{Cloudless}}(\lambda = 350, \theta) = (0.698 \pm 0.036) \cos\theta^{(1.44 \pm 0.06)}, \tag{16}$$

where the coefficient of determination was always higher than 0.98 and the error of the coefficients represents the expanded uncertainty (k = 2).

The Brewer cloud-free measurements for 305 nm depend on total ozone amount, and, thus, Eq. (14) should be calculated only for a certain total ozone amount. In this work, the total ozone amount values were quite homogenous (between 298 and 320 DU). If the total ozone amount changes broadly during the analyzed period, then it would be more adequate to utilize the semiempirical cloud transmittance A for 324 nm to correct the Brewer measurements at 305 nm.

When the semiempirical cloud transmittance A is determined, the f_g global correction factor can be obtained for each measurement by the interpolation in the LUT. To apply the angular response correction, the Brewer measurements must be divided by the f_g global correction factor.

Figure 7 shows the ratios between the Brewer and QASUME measurements of the spectral UV irradiances at 305, 324, and 350 nm. The ratios are calculated using corrected and original Brewer measurements for three datasets (cloud free, cloudy, and all cases):

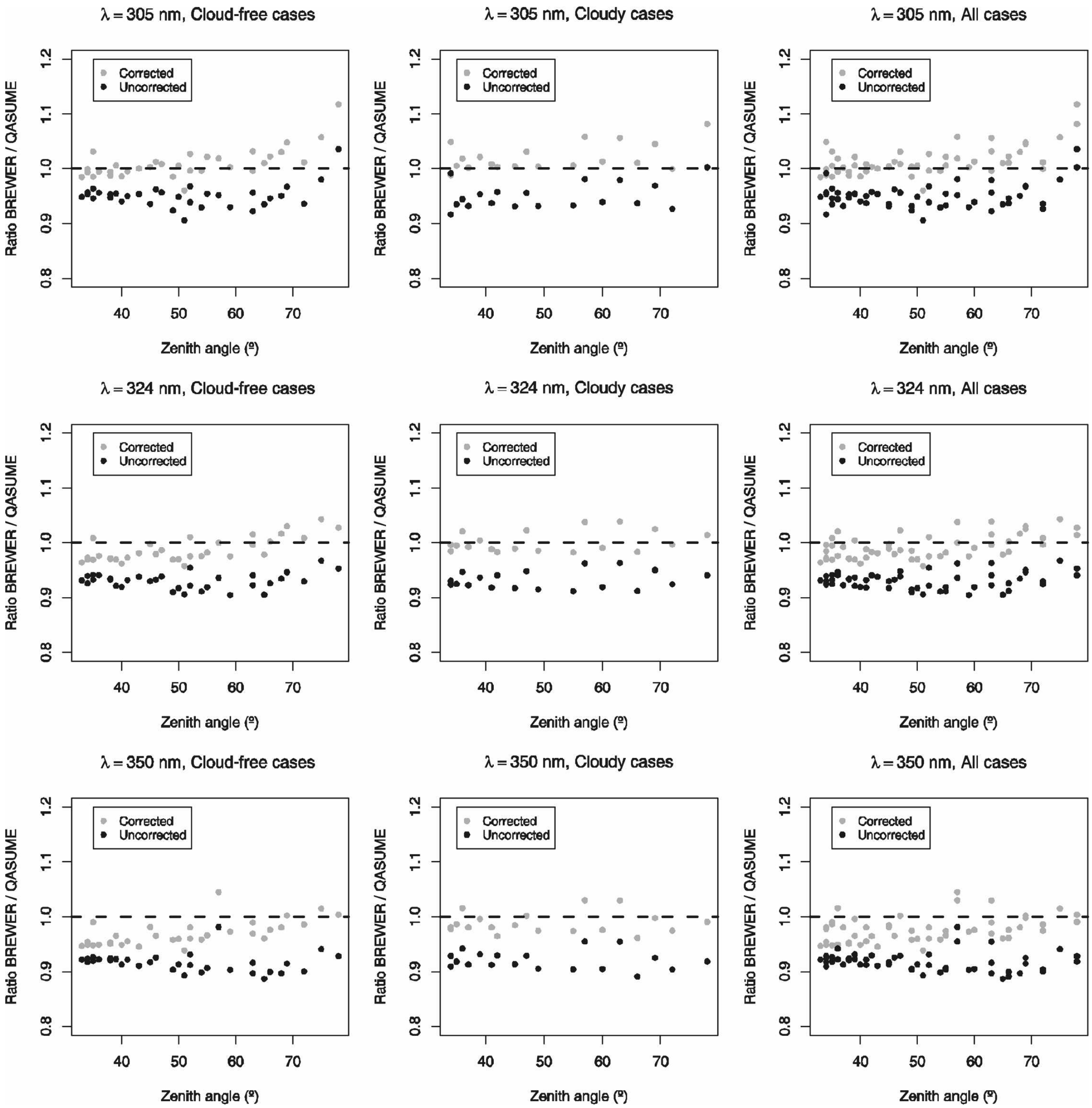

FIG. 7. Spectral irradiance ratios of Brewer–QASUME at three wavelengths for corrected and uncorrected Brewer data.

$$r_{\text{Original}} = \frac{E^{\text{BREWER}}_{\text{Original}}}{E^{\text{QASUME}}},$$

$$r_{\text{Corrected}} = \frac{E^{\text{BREWER}}_{\text{Original}}/f_g}{E^{\text{QASUME}}} = \frac{E^{\text{BREWER}}_{\text{Corrected}}}{E^{\text{QASUME}}}. \quad (17)$$

It is evident that the application of the angular response correction improves the results; that is, the corrected data are in better agreement with the reference data than they are with the uncorrected values. The mean absolute relative bias error (MABE) is used as a measure of the quality of the cosine correction defined. This parameter is calculated using data over all solar zenith angles and it is defined as

$$\text{MABE} = \frac{|E^{\text{BREWER}} - E^{\text{QASUME}}|}{E^{\text{QASUME}}}. \quad (18)$$

Table 1 shows the MABE parameters for the three datasets using corrected and uncorrected Brewer data

TABLE 1. The MABE for cloud-free, cloudy, and all cases using corrected and uncorrected Brewer data at 305, 324, and 350 nm.

	MABE (cloud-free cases)		MABE (cloudy cases)		MABE (all cases)	
	Corrected (%)	Uncorrected (%)	Corrected (%)	Uncorrected (%)	Corrected (%)	Uncorrected (%)
λ = 305 nm	2.1	5.2	2.6	5.0	2.3	5.1
λ = 324 nm	2.3	7.0	1.6	6.8	2.0	6.9
λ = 350 nm	3.2	8.8	2.0	8.0	2.9	8.5

at 305, 324, and 350 nm. The relative error is higher for cloud-free cases than cloudy conditions when uncorrected Brewer measurements were used. In addition, it can be seen that the correction method presented in this paper contributes to a reduction in the differences between the Brewer spectroradiometer and the reference instrument by a factor higher than 2 for cloud-free and also for cloudy conditions. The remaining differences are lower than the uncertainties attributed to both instruments and could be due to the uncertainties of the correction method (angular response, model estimations, and isotropy assumption).

Figure 7 shows that the r_{Original} values for cloud-free conditions decrease with the zenith angle until approximately SZA = 65°. In addition, it can be seen that the correction removes this angular dependence of the difference with the QASUME reference instrument. For solar zenith angles higher than 65°, the $r_{\text{Corrected}}$ values show a slight angular dependence caused by uncertainties in the correction method for high zenith angles. On the other hand, Fig. 7 also shows that for cloudy cases, the difference with the QASUME reference instrument depends on the solar zenith angle for neither the corrected nor the uncorrected data. This fact is due to the constant value of the global correction factor for cloudy conditions.

Figure 7 shows that the correction depends on that wavelength with worse agreement for longer wavelengths especially at low solar zenith angles. The global correction factor only depends on wavelength by variable R [Eq. (4)]. This variable is higher for longer wavelengths due to the increase of the direct component in the global UV irradiance (Fig. 2). Therefore, the global correction factor presents higher values for longer wavelengths and a smaller correction over the Brewer measurements.

5. Conclusions

In this paper, a methodology for the angular response correction has been presented. The following conclusions can be drawn:

The uncertainties of Brewer measurements due to the nonideal angular behavior depend on the wavelength, solar zenith angle, and sky conditions. Thus, this angular response error is about 6% for cloudy conditions and from 2% to 9% for cloud-free conditions. Therefore, suitable correction methods are necessary for improving the accuracy of the measurements.

Uncorrected and corrected Brewer data were compared with simultaneous measurements of the transportable QASUME reference spectroradiometer. The results indicated that corrected Brewer data could reduce the differences with respect to the reference values by a factor higher than 2. This fact shows that the correction method addressed in this paper is suitable for reducing the angular response error.

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REFERENCES

Bais, A. F., 1997: Absolute spectral measurements of direct solar ultraviolet with a Brewer spectrophotometer. *Appl. Opt.,* **36,** 5199–5204.

——, S. Kazadzis, D. Balis, C. S. Zerefos, and M. Blunthaler, 1998: Correcting global solar ultraviolet spectra recorded by a Brewer spectroradiometer for its angular response error. *Appl. Opt.,* **37,** 6339–6344.

——, and Coauthors, 2005: Portable device for characterizing the angular response of UV spectroradiometers. *Appl. Opt.,* **44,** 7136–7143.

Bernhard, G., and G. Seckmeyer, 1999: Uncertainty of measurements of spectral solar UV irradiance. *J. Geophys. Res.,* **104,** 14 321–14 345.

——, C. R. Booth, and J. C. Ehramjian, 2003: The quality of data from the National Science Foundation's UV Monitoring Network for Polar Regions. *Proc. SPIE,* **4896,** 79–93.

Blumthaler, M., J. Grobner, M. Huber, and W. Ambach, 1996: Measuring spectral and spatial variations of UVA and UVB sky radiance. *Geophys. Res. Lett.,* **23,** 547–550.

Diffey, B. L., 1991: Solar ultraviolet radiation effects on biological systems. *Phys. Med. Biol.,* **36,** 299–328.

Feister, U., R. Greve, and K. Gericke, 1997: A method for correction of cosine errors in measurements of spectral UV irradiance. *Solar Atomic Energy,* **60,** 313–332.

Fioletov, V. E., L. McArthur, J. E. Kerr, and D. I. Wardle, 2001: Long-term variations of UV-B irradiance over Canada estimated from Brewer observations and derived from ozone

and pyranometer measurements. *J. Geophys. Res.,* **106,** 23 009–23 028.
——, J. E. Kerr, D. I. Wardle, N. Krotkov, and J. R. Herman, 2002: Comparison of Brewer ultraviolet irradiance measurements with total ozone mapping spectrometer satellite retrievals. *Opt. Eng.,* **41,** 3051–3061.
Gröbner, J., and P. Sperfeld, 2005: Direct traceability of the portable QASUME irradiance scale to the primary irradiance standard of the PTB. *Metrologia,* **42,** 134–139.
——, M. Blumthaler, and W. Ambach, 1996: Experimental investigation of spectral global irradiance measurements errors due to a non ideal cosine response. *Geophys. Res. Lett.,* **23,** 2493–2496.
——, and Coauthors, 2005: Traveling reference spectroradiometer for routine quality assurance of spectral solar ultraviolet irradiance measurements. *Appl. Opt.,* **44,** 5321–5331.
——, M. Blumthaler, S. Kazadzis, A. Bais, A. Webb, J. Schreder, G. Seckmeyer, and D. Rembges, 2006: Quality assurance of spectral solar UV measurements: Result from 25 UV monitoring sites in Europe, 2002 to 2004. *Metrologia,* **43,** S66–S71.
Josefsson, W., 1986: Solar ultraviolet radiation in Sweden. SMHI Rep. 53, Norrköping, Sweden, 79 pp.
Kimlin, M. G., J. Sabburg, A. V. Parisi, and R. S. Meltzer, 2003: Comparison of Brewer spectrophotometer ultraviolet data from similar latitudes in the Northern and Southern Hemisphere. *J. Atmos. Sol.-Terr. Phys.,* **65,** 1401–1410.
Mayer, B., and A. Kylling, 2005: The libRadtran software package for radiative transfer calculations—Description and examples of use. *Atmos. Chem. Phys.,* **5,** 1319–1381.
Seckmeyer, G., and G. Bernhard, 1993: Cosine error correction of spectral UV irradiances. *Proc. SPIE,* **2049,** 140–151.
Toledano, C., 2005: Aerosol climatology by means of optical properties and air mass characterization at El Arenosillo AERONET site (in Spanish). Ph.D. dissertation, Universidad de Valladolid, Valladolid, Spain, 237 pp.
Vilaplana, J. M., 2004: Measurement and analysis of ozone and UV solar radiation at El Arenosillo-INTA (Huelva, Spain) (in Spanish). Ph.D. thesis, Universidad de Valladolid, Valladolid, Spain, 247 pp.
WMO, 1997: Instrument to measure solar ultraviolet radiation. Global Atmosphere Watch Tech. Rep. 125, 51 pp.
——, 2003: *Scientific Assessment of Ozone Depletion: 2002 Global Ozone Research and Monitoring Project.* Global Ozone Research and Monitoring Project Tech. Rep. 47, 498 pp.
Zeng, J., R. L. McKenzie, K. Stammes, M. Wineland, and J. Rosen, 1994: Measured UV spectra compared with discrete ordinate method simulations. *J. Geophys. Res.,* **99,** 23 019–23 030.