Improving solar ultraviolet irradiance measurements by applying a temperature correction method for Teflon diffusers

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To establish trends in surface ultraviolet radiation levels, accurate and stable long-term measurements are required. The accuracy level of today's measurements has become high enough to notice even smaller effects that influence instrument sensitivity. Laboratory measurements of the sensitivity of the entrance optics have shown a decrease of as much as 0.07–0.1%/deg temperature increase. Since the entrance optics can heat to greater than 45 °C in Dutch summers, corrections are necessary. A method is developed to estimate the entrance optics temperatures from pyranometer measurements and meteorological data. The method enables us to correct historic data records for which temperature information is not available. The temperature retrieval method has an uncertainty of less than 2.5 °C, resulting in a 0.3% uncertainty in the correction to be performed. The temperature correction improves the agreement between modeled and measured doses and instrument intercomparison as performed within the Quality Assurance of Spectral Ultraviolet Measurements in Europe project. The retrieval method is easily transferable to other instruments. © 2007 Optical Society of America

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1. Introduction

Solar ultraviolet (UV) radiation reaching the Earth's surface is monitored worldwide. This is primarily driven by the increase of UV levels that are due to anthropogenic destruction of stratospheric ozone, and its associated adverse health and environmental effects. To detect global trends, stable and comparable measurements are required. With the mobile reference spectroradiometer (QASUME) [1–3], Quality Assurance of Spectral Ultraviolet Measurements in Europe an instrument is provided that tracks the stability of other spectroradiometers directly at their homesite. It serves as a reference instrument that travels to different monitoring sites in Europe. A comparison with the primary irradiance standard (blackbody BB3200pg) of the Physikalisch Technische Bundesanstalt shows the uncertainty to be 2.5% in the UV spectral range and 2% above 400 nm wavelength [3].

The National Institute for Public Health and the Environment (RIVM) operates two spectroradiometers for monitoring purposes, one is installed in a mobile container (called RIVM1 in the following), the other is mounted on the roof of the RIVM (called RIVM2 here). A comparison between the mobile spectroradiometer and the QASUME traveling spectroradiometer (here called QASUME), conducted in Bilthoven, The Netherlands, in 2003 revealed a diurnal variation between both instruments, especially on warm days. In clear sky conditions, when the air temperature reached values of 30 °C, the deviation between both instruments was 3% higher than in the morning or afternoon hours and on colder days with cloudy conditions. The temperature of the QASUME entrance optics was kept at 25 ± 2.5 °C [1], therefore the diurnal variations were assigned to a temperature sensitivity of the RIVM1 diffuser. This kind of

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temperature sensitivity was already reported by Ylianttila and Schreder [4] who found transmittance changes between −0.015%/°C and −0.1%/°C depending on the type of Teflon diffuser used in the entrance optics.

Until May 2006, the temperatures of the RIVM1 diffuser (T_{dif}) were recorded only during a short period in July and August 2004, therefore, a surrogate for all the other measurements outside this period is needed. Moreover, Teflon diffusers are commonly used for UV irradiance measurements, hence, a commonly applicable corrections algorithm is most welcome to correct other data sets that might have suffered from temperature variations.

In Section, 2 we quantify the temperature dependence of the two RIVM diffusers. The temperature retrieval method is presented in Section 3 and tested against temperature measurements for the period from May to August 2006 in Section 4. Validation of the correction on UV data is also presented in Section 4.

2. Quantification of the Temperature Dependence

A. Instrumental

The RIVM spectrometers are temperature stabilized at 20 °C. The entrance optics consist of a flat Teflon diffuser (Bentham, 0.5 mm thick), which is kept at 25 °C minimum, i.e., only heating, no cooling, can be applied. A standard wavelength scan covers 285–380 nm in 0.5 nm steps, the full width at half-maximum is 0.32 nm. Five spectra per hour are measured from sunrise to sunset. In addition, the global solar radiation is monitored continuously by a Kipp and Zonen CM21 pyranometer sampled at 1 Hz. Each minute, the average and the standard deviation are stored. Further information about the setup is given elsewhere [5].

B. Experimental

The influence of temperature on the sensitivity of the spectroradiometer was studied for temperatures of the diffuser T_{dif} between 25 °C and 45 °C in the laboratory. The heating was realized with the temperature controller. Changes in the sensitivity were measured using a 250 W lamp as the radiation source. The diffuser was placed in front of the lamp mounted in a housing that protects the lamp from outdoor temperature changes and collimates the lamp output. During the measurements, the current and voltage of the lamp were monitored. The variability of the lamp current was approximately 0.001%, so that changes in the lamp output that are due to an unstable current can be neglected.

Spectra were measured covering 285 and 375 nm wavelengths in 5 nm steps. This larger step size conveniently reduced the total scan time to 3 min and still allowed for identification of a possible wavelength dependency. Starting at 25 °C, the temperature was increased in steps of 2–3 °C. The whole experiment was performed only during the heating cycle, as the cooling to a desired temperature lasted too long. Two spectral scans were performed for each

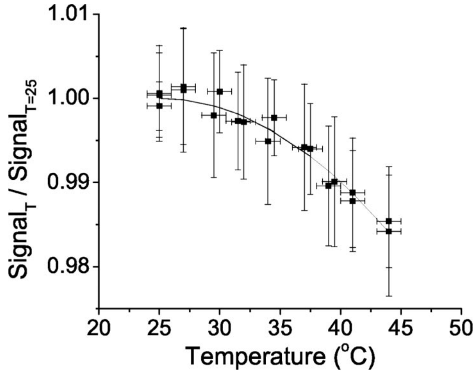

Fig. 1. Ratio of signals measured at different temperatures of the RIVM1 diffuser with reference to the lamp signal measured at T_{dif} = 25 °C.

temperature. The temperature values at the beginning and at the end of the spectral scans were recorded; they did not differ by more than 1 °C. As a check the temperature were also measured at different positions on the entrance optics and were well within a 2 °C range. Thus, a homogeneous temperature distribution of the entrance optics may be assumed during the experiment.

Each spectrum is compared to the 25 °C situation as the spectrometer operates normally with an entrance optics temperature of 25 °C minimum. Figure 1 shows the wavelength-averaged ratios of the different spectra for the RIVM1 instrument. The horizontal error bars indicate the uncertainty of the diffuser temperature (1 °C); the vertical error bars represent the statistical variation within the wavelength scan. Overall, the ratio decreases with increasing temperature of the order of 0.07%/°C, meaning that during operation irradiances are underestimated on warm and hot days. Similar studies performed by Ylianttila and Schreder [4], also using a Bentham Teflon flat diffuser, yielded a similar temperature dependence of 0.05%/°C.

For the RIVM1 diffuser, a temperature dependence below 30 °C is not observed, and a second-order polynomial is used to describe the data. Tests with the RIVM2 spectroradiometer system revealed a dependence ranging between 0.10%/°C and 0.14%/°C. For this Teflon diffuser the best relationship between T_{dif} and the spectroradiometer sensitivity is achieved with a set of linear fits (see Fig. 2). The data in Fig. 2 were averaged over a wavelength range of 30 nm to reduce the statistical variation. The sensitivity of RIVM2 has a distinctive wavelength dependency, as shown in Fig. 2 (coefficients of determination R^2 = 0.85–0.98), with a stronger decrease of the sensitivity for shorter wavelengths, whereas the RIVM1 does not show a significant dependency (R^2 = 0.2). In particular, for high diffuser temperatures the difference in sensitivity at 300 and 400 nm for RIVM2 can be greater than 1%. This observation shows that the temperature behavior cannot be determined *a priori* from information on design but should be determined by a direct experiment.

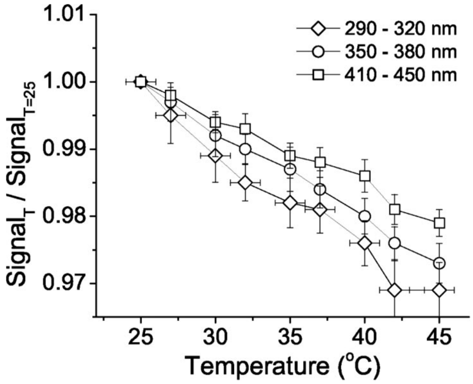

Fig. 2. Ratio of signals measured at different temperatures of the RIVM2 diffuser with reference to the lamp signal measured at $T_{\mathrm{dif}} = 25$ °C. The vertical error bars indicate the standard deviations of the wavelength averaging.

3. Temperature Retrieval

For periods when T_{dif} is not recorded, a proxy or an indirect method must be found. The diffuser will heat up primarily by direct radiation of the Sun. Thus in Fig. 3 we plot the measured temperature of the RIVM1 diffuser and the global solar irradiance, measured by a pyranometer, as a function of time. It is readily observed that T_{dif} (dotted line) is delayed compared to the solar irradiance F (solid line), and the temperature line follows a smoothed version of the solar irradiance pattern. For the sake of the argument, let us first assume that we have a constant heat exchange rate γ (in units of s^{-1}) between the diffuser and its environment, and that heating is driven only by the irradiation of the sun, $F(t)$ (in units of W $m^{-2}nm^{-1}$). Then for the diffuser temperature $T(t)$ at time t we can write the differential equation

$$\frac{\mathrm{d}T(t)}{\mathrm{d}t} = -\gamma[T(t) - T_{\mathrm{sur}}] + \alpha F(t), \tag{1}$$

The dif index is omitted here for convenience, αF (in units of °C s^{-1}) describes the temperature rise rate that is due to irradiance F, and T_{sur} denotes the temperature of the surrounding medium with which the diffuser has a thermal coupling, i.e., the outside air and the building on which it is mounted. Next we note

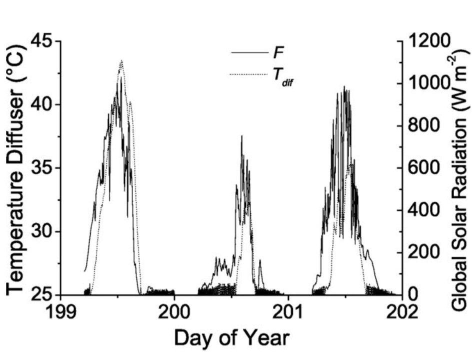

Fig. 3. Solar global radiation F and temperature of the diffuser T_{dif} for days 199–201 in 2004.

that the diffuser temperature cannot follow the fast fluctuations in the solar irradiance induced by clouds. Hence, it makes sense to write the irradiance $F(t)$ as a sequence of discrete levels and equidistant steps Δt; at each level the irradiance is constant, i.e., F_n. (In the end, this is exactly what is available, i.e., the 1 min integrated pyranometer data $\Delta t = 60$ s). The general solution can now be written as

$$T_n(t) = \left[T_n{}^0 - \left(\frac{\alpha F_n}{\gamma} + T_{\mathrm{sur}}\right)\right] e^{-\gamma[t-(n-1)\Delta t]} + \left(\frac{\alpha F_n}{\gamma} + T_{\mathrm{sur}}\right) \tag{2}$$

for $(n - 1)\Delta t \leq t \leq n\Delta t$, where the surrounding temperature is also assumed to be constant. Demanding a continuous transition of $T_n(t) = T_{n-1}(t)$ at $t = (n - 1)\Delta t$ readily yields the following expression for temperature T_N at the actual observation time of $N\Delta t$:

$$T_N(t = N\Delta t) = T_{N+1}{}^0 = \sum_{n=1}^{N} (1 - e^{-\gamma\Delta t}) e^{-\gamma\Delta t(N-n)} \times \left(\frac{\alpha F_n}{\gamma} + T_{\mathrm{sur}}\right). \tag{3}$$

We thus see that each irradiance level F_n is weighted exponentially with respect to the time of observation, $\exp[-\gamma\Delta t(N - n)]$. In reality, heating the diffuser is done directly by solar irradiation but also through heat coupling with its container or the roof of the building. The outside air temperature varies and might have either a cooling or heating effect. Other factors, such as humidity, total heated mass, and local wind speed, leave us with to many unknown variables. Furthermore, a temperature approximation by use of only one or two additional quantities will be more suitable for applications elsewhere. We thus boldly write the diffuser temperature as

$$F_N(t = N\Delta t) = C_1 F_w + C_2(T_{\mathrm{air}},\ T_{\mathrm{roof}},\ \text{windspeed}, \ldots)$$

with

$$F_w = \sum_0^N F_n e^{-\gamma(N-n)\Delta t}. \tag{4}$$

The correlation coefficients between the weighted irradiance F_w and T_{dif} are now calculated for several decay times γ^{-1} of 30–100 min for each individual day, which will eventually determine coefficients C_1 and C_2. A test period from July to August 2004 is used for which measurements of the entrance optics temperature are available. The best results are obtained with a decay time of 70 min ($R^2 = 0.94$) as shown in Fig. 4(a). As expected, T_{dif} increases linearly with increasing F_w, and the point at which T_{dif} deviates from the 25 °C level varies from day to day. Returning to Fig. 3, we readily learn that the maxima of T_{dif} on days 199 and 201 differ significantly by 7 °C because the outside air temperatures differ on these

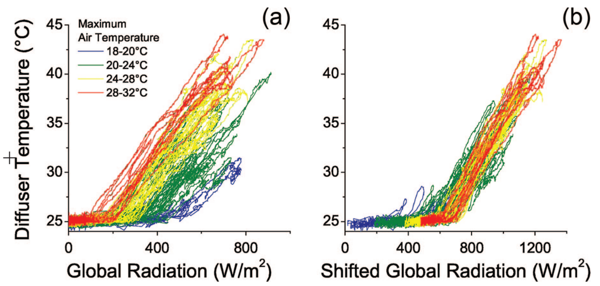

Fig. 4. (a) Weighted and (b) shifted weighted solar irradiances versus the diffuser temperature. The data are shown for several $T_{\max}$ bins.

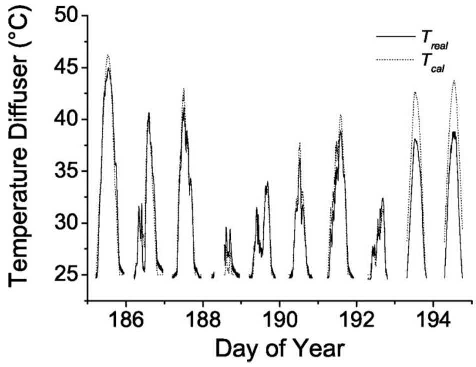

Fig. 5. Measured and retrieved diffuser temperatures for the period from 4 to 14 July 2006.

two days. The maximum air temperature was 29 °C and 22 °C, and the maxima of the global radiation were of the same magnitude (approximately 1000 W m^{-2}). This daily maximum air temperature $T_{\max}$, as provided by the Royal Dutch Meteorological Institute (KNMI), turns out to be a good discriminator for the point at which T_{dif} starts to deviate from 25 °C. In Fig. 4(a) we have binned the curves with respect to the maximum outside air temperature $T_{\max}$. It is obvious that heating the diffuser starts at a higher solar irradiation for lower maximum air temperatures.

The weighted solar irradiance F_w is now shifted, depending on $T_{\max}$ of each day, to condense all the curves to one general curve [see Fig. 4(b)] allowing us to express the diffuser temperature as

$$T_{\text{dif}} = b_0 + b_1 F_{\text{shift}}. \qquad (5)$$

The necessary shift of the weighted solar irradiance sums F_w follows an exponential function of the maximum outside temperature and was determined by considering the crossings of the $T_{\text{dif}} = 30$ °C line and the F_w curves. The line $T_{\text{dif}} = 30$ °C is somewhat arbitrary but it is the midpoint between a true temperature increase and a corresponding drop of sensitivity. Having this region well described by the algorithm will result in an overall good performance of the temperature correction. Improvements at the cost of more parameters might be made here but, as follows from Fig. 4(b), just the maximum temperature already works satisfactorily. Also, similar results can be obtained by using the average day temperature instead of the maximum day temperature, indicating that the introduction of more temperature readings or a temperature profile will marginally improve the result. The coefficients $b_0 = 9.153$ °C and $b_1 = 0.026$ m^2 W^{-1} for Eq. (5) follow from Fig. 4(a) and are determined for $T_{\text{dif}} \geq 30$ °C.

4. Application

A. Temperature Retrieval Validation

The measured values of the RIVM1 diffuser temperature (T_{real}) and the calculated data (T_{cal}) are compared for an independent data set that was collected from May to August 2006. Figure 5 shows the measured and retrieved temperatures for the period from 4 to 14 July 2006 (days 185–194). It is clear that the diurnal pattern of T_{dif} is well reproduced. Periods of high temperatures as well as periods of temperatures near 25 °C agree to within ±2 °C (±1 °C without days 193 and 194). Overall, T_{dif} can be reproduced with an uncertainty of ±2.0 °C, which corresponds to an uncertainty of the sensitivity of 0.2%. Table 1 presents the difference $T_{\text{real}} - T_{\text{cal}}$ for two temperature ranges: (i) 25 °C ≤ T_{real} ≤ 30 °C and (ii) T_{real} ≥ 30 °C. Most of the data points are within 25 °C ≤ T_{real} ≤ 30 °C, for which the temperature dependence is quite small. In this range the standard deviation (stdev) of the measured and calculated temperatures is smaller (stdev = 1.3 °C) than for the data with T_{real} ≥ 30 °C (stdev = 2.4 °C), where the temperature dependence is more crucial.

B. Intercomparison Results of UV Radiation

The effect of correcting spectral UV measurements in terms of their temperature dependence was studied for data collected during the intercomparison between QASUME and RIVM1 in 2003 and in 2006. Daily UV sums were calculated from the erythemally weighted irradiance measurements using the action spectrum by McKinley and Diffey [6]. Table 2 summarizes the ratios of the UV sums that were derived from the two spectroradiometers. The different ratios are based on two RIVM1 data sets, one without temperature correction and the other with applied correction. In addition the maximal temperature of the diffuser and maximum outside air temperature $T_{\max}$ is given. On days 195–197 in 2003 the temperature of the diffuser rose above 40 °C, which contributes to the deviation of −3% for the uncorrected RIVM1 data. Applying the correction gives a deviation of −1% on all days in 2003, which is in agreement with the results based on the uncorrected RIVM1 data for

Table 1. Comparison of Measured and Retrieved Temperatures

Data	Mean Difference $T_{\text{real}} - T_{\text{cal}}$	Stdev	Number of Cases
25 °C ≤ T_{real} ≤ 30 °C	0.2	1.3	33100
T_{real} ≥ 30 °C	−0.4	2.4	23500

Table 2. Comparison of Daily UV Sums

Year	Day	max T_{dif} (°C)	T_{max} (°C)	RIVM1/QASUME Uncorrected	RIVM1/QASUME Corrected
2006	185	46	32	0.94	0.97
2006	186	40	30	0.95	0.97
2006	187	42	28	0.95	0.97
2003	195	44	28	0.97	0.99
2003	196	46	31	0.97	0.99
2003	197	45	34	0.97	0.99
2003	198	25	20	1.01	1.01
2003	199	33	25	0.99	0.99

the colder days 198 and 199. For days 196, 197, and 198 the diurnal pattern of the wavelength-averaged ratios between RIVM1 and QASUME are shown in Fig. 6. As expected the largest deviations between the QASUME and the RIVM1 uncorrected data occur at midday. Applying the temperature corrections brings the agreement to a 1% level. A residual pattern can also emerge from the different angular response of the QASUME and RIVM1 diffuser, even if a so-called cosine correction to RIVM1 has been applied. Day 198 shows a larger scatter that is due to the fractional cloudiness that occurred on that day. In 2006 the QASUME and the RIVM1 instrument was not placed directly at the same location as in 2003. A distance of 200 m and a different field of view possibly cause the slightly higher deviation of −3% between the corrected RIVM1 and the QASUME UV sums. However, correcting the temperature dependence results in a 2–3% improvement of the agreement.

Figure 7 shows a comparison between measured and modeled erythemally weighted UV doses for clear sky days. The model as described in den Outer *et al.* [5] is used. Seventeen summer mid-year days (days between 120 and 240) could be selected from the RIVM ten year data record when clouds did not occur during the whole day. Averaged ratios of measured to modeled doses are shown as a function of time during the day. We show ratios for uncorrected

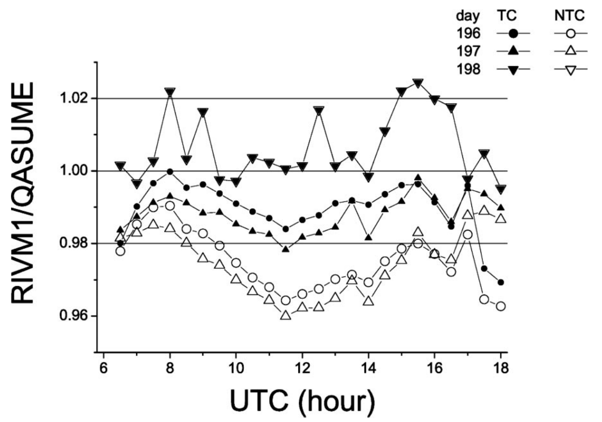

Fig. 6. Comparison of RIVM1 and QASUME with correction (TC) and without correction (NTC) of temperature dependence for days 196–198 in 2003.

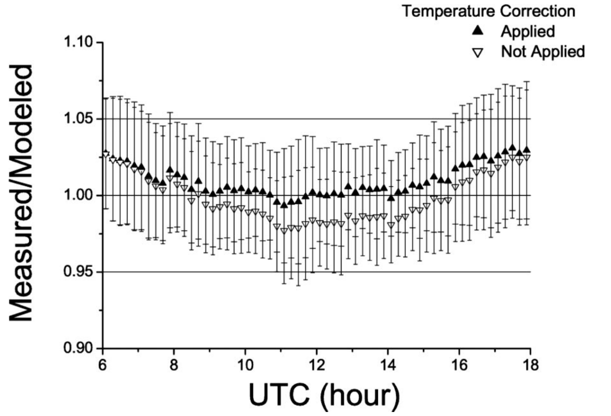

Fig. 7. Comparison of measured and modeled erythemal doses for clear sky days. Open triangles: temperature correction not applied; filled triangles, correction applied.

and temperature-corrected measurements. Clearly, the dip around noon is removed by the introduction of the temperature correction. On average, the model seems to yield an underestimation, which can be attributed to the fixed aerosol load used in the model calculation.

5. Summary and Conclusion

A method has been presented that retrieves entrance optics temperatures using only 1 min average pyranometer data and maximum outside air temperatures as input data. Knowledge of the entrance optics temperature becomes essential as the transmission of diffusers, and hence the sensitivity of spectroradiometers turn out to be temperature dependent. In Dutch summers the entrance optics may heat to as much as 20 deg and exceed 45 °C, resulting in a sensitivity decay that ranges between 1.4 and 3% depending on the actual diffuser.

The temperature retrieval is accurate to 2.5 °C and is applicable to other instruments and locations as well. Corrected measurements indeed show an improved agreement when compared with other temperature-stabilized instruments or compared with modeled values.

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