JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. D23, 4676, doi:10.1029/2001JD001565, 2002

Comparisons of corrected daily integrated erythemal UVR data from the U.S. EPA/UGA network of Brewer spectroradiometers with model and TOMS-inferred data

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Received 3 December 2001; revised17 April 2002; accepted 15 June 2002; published 3 December 2002.

[1] A network of 21 Brewer spectroradiometers, owned by the U.S. Environmental Protection Agency (U.S. EPA) and operated by the University of Georgia (UGA), is measuring ultraviolet (UV) spectral irradiances throughout the United States. Corrections to the raw data for 4 of the 21 Brewers have now been implemented. These corrections include (1) the stray light rejection, (2) the cosine errors associated with the full sky diffuser, (3) the temperature dependence of the response of the instruments, and (4) the temporal variation in the instrument response due to changes in the optical characteristics of the instruments. While for many sites the total corrections amount to less than 10%, for certain sites they are much larger, in some cases amounting to more than 25%. It is estimated that application of these corrections brings the uncertainty of the absolute irradiance of individual spectral scans to approximately 6% for all known major sources of error for all solar zenith angles. A comparison is presented of corrected daily integrated erythemal UV doses on clear days to both model and Total Ozone Mapping Spectrometer (TOMS) UV values. The TOMS retrievals show a positive bias with respect to the measured values that falls in the range of 12.5–1.4% with an average value of 5% for the four sites studied.z *INDEX TERMS:* 7549 Solar Physics, Astrophysics, and Astronomy: Ultraviolet emissions; 7538 Solar Physics, Astrophysics, and Astronomy: Solar irradiance

Citation: Sabburg, J., J. E. Rives, R. S. Meltzer, T. Taylor, G. Schmalzle, S. Zheng, N. Huang, A. Wilson, and P. M. Undelhofen, Comparisons of corrected daily integrated erythemal UVR data from the U.S. EPA/UGA network of Brewer spectroradiometers with model and TOMS-inferred data, *J. Geophys. Res.*, *107*(D23), 4676, doi:10.1029/2001JD001565, 2002.

1. Introduction

[2] Satellite observations of spectrally resolved reflectivity are presently used to infer surface ultraviolet radiation (UVR) over much of the Earth's surface. The wide coverage afforded by such estimates makes these results extremely useful. It is therefore important that a validation of these satellite-inferred surface UVR values be performed. There have been a number of studies that have compared ground-based to satellite-inferred UVR data [*Krotkov et al.*, 1998, 2001; *Herman et al.*, 1999; *Udelhofen et al.*, 1999; *Wang et al.*, 2000; *Udelhofen et al.*, 2000; *Kalliskota et al.*, 2000; *Martin et al.*, 2000; *McKenzie et al.*, 2001]. These studies involve locations from both the Northern Hemisphere and Southern Hemisphere with latitudes ranging from approximately 13 to 70°, and altitudes from 50 to 2960 m. In most cases, it has been found that the satellite-based estimates exceed the values measured by the ground-based instruments. Since a portion of this difference may result from errors in the ground-based values, it is important that the ground-based measurements be of the highest possible absolute accuracy. In the present study a comparison is made with ground-based UVR measurements from four sites in a network of 21 Brewer MKIV spectroradiometers. These are the first four sites for which the UVR results have been corrected for the major contributions to their errors. It will eventually be possible to use data from all 21 sites to improve the evaluation of the satellite retrievals.

[3] In a recent study of four sites, *McKenzie et al.* [2001] found that for the two sites in Europe, the satellite estimates of daily integrated erythemal doses, referred to here as DUV, exceed those of the ground-based measurements by 20–30% and that for the Toronto site the overestimate is about 15%. Only at the pristine site in Lauder, NZ in the

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0148-0227/02/2001JD001565$09.00

Table 1. Brewer Station Information (TOMS data are also shown as [ ])

					Sky conditions for TUVSPEC		
						Aerosol optical depth (340 nm)	
Station	Brewer no.	Latitude	Longitude	Elevation, m	Visibility, km	Spring–Summer	Fall–Winter
Boulder	101	40.12 [40.02]	−105.24 [−105.25]	1689 [1390]	64.4	0.12	0.08
Rocky Mt.	146	40.03 [40.02]	−105.53 [−105.25]	2896 [1390]	64.4	0.09	0.05
Gaithersburg	105	39.13 [39.13]	−77.22 [−77.21]	20 [130]	17.0	0.72	0.67
RTP	087	35.89 [35.89]	−78.88 [−78.87]	134 [123]	16.1	0.72	0.67

southern hemisphere is the agreement within a few percent. They therefore conclude that the stated accuracy of satellite retrievals of UV (±12%) is overly optimistic.

[4] *Herman et al.* [1999] found a similar difference of about 20% with a Brewer at Toronto for spectrally resolved irradiances measured at the time of satellite overpass during the Summer months. They have made a detailed analysis of the sources of error that explains much of the difference. A total systematic error of 22% is estimated due to a combination of undetected urban ground haze (Total Ozone Mapping Spectrometer (TOMS) 3% too high), omitted absorbing aerosol (TOMS 8% too high), cosine error of Brewer (Brewer 6% too low) and the slit function used in the TOMS model (TOMS 5% too high). Another comparison was reported by *Kalliskota et al.* [2000], involving erythemally weighted UV doses comparing the Nimbus 7/TOMS measurements and ground-based measurements using a SUV-100 double monochromater for three sites. Two of these were at high latitudes (Ushuaia in Argentina and Palmer in Antarctica) and one was at midlatitudes (San Diego, CA). The ground based instruments were temperature controlled so that temperature corrections were unnecessary but the data was not corrected for the cosine error of the input diffuser. The results for San Diego, where surrounding snow was not a problem, indicated a 25% overestimate by the TOMS retrieval. Even including a 6% correction to the ground-based results for the cosine correction still leaves a large (19%) difference, but without a characterization of the angular response of the diffuser, the proper correction is really uncertain.

[5] *Wang et al.* [2000] compared satellite retrieval of UV-B with Brewer ground-based measurements at the time of overpass for four sites in Canada, based on a new algorithm. A 6% correction was applied to the Brewer data to compensate for the cosine error and the satellite estimates used aerosol optical depth values determined either on a daily basis using Langley plots for the Toronto site or using a typical single value for the other sites. The agreement between the satellite retrievals and ground-based values of UV-B suggests a validation of the new algorithm for estimating surface UV-B from satellite measurements. However, as shown by *Martin et al.* [2000], the uncertainty of daily UV doses based on a single daily satellite measurement are subject to large uncertainties because of changes in atmospheric conditions during the day and these conditions can be quite different from those at the time of overpass. Temporally averaged data show much better agreement but for the two sites studied, under clear-sky conditions, systematic overestimates by TOMS of 10–15% were observed.

[6] In order to effectively evaluate satellite retrievals of surface UVR, it is necessary to obtain the most accurate ground-based measurements possible. In this paper, the Brewer spectroradiometers that provide the ground-based data have been corrected for what are believed to be all their major sources of error. The cosine correction is obtained from an instrument characterization of the angular dependence of the response and the correction is specified as a function of the SZA. Although the 6% correction applied in a number of the studies described above is reasonable, based on our experience with 21 instruments, the actual correction can vary between 2 and 12% depending on instrument and SZA at the time of measurement. This results in an error that can be as large as 12% for any given measurement when the canonical 6% value is used instead of the true correction. In addition, the data is corrected for the temperature dependent response of the instrument. This correction is typically 0.2–0.3%/°C. Since these instruments are not temperature stabilized, their internal temperatures typically range from about 0 to 50°C. This results in a variation of up to 10–15% in response for a typical instrument; even larger temperature dependencies are seen in some instruments.

[7] This study is useful in that it provides an additional, spectral UV database to that which is currently available that will eventually encompass 21 sites spanning latitudes from 18.3°N to 63.7°N. In this present study DUV data is evaluated from four of these 21 sites that use Brewer MKIV spectroradiometers (Kipp & Zonen Inc, Canada). The database from these sites extends for periods ranging from two to seven years. Both uncorrected and corrected DUV data are compared with a clear-sky UV model and to TOMS-inferred DUV values on clear days. All DUV data, Brewer, model and TOMS-inferred, used the same action spectrum of *McKinlay and Diffey* [1987]; however, there were slightly different latitudes, longitudes and altitudes used in producing the TOMS-inferred data. The four sites were Table Mountain (Boulder), Niwot Ridge (Rocky Mt.), Gaithersburg and Research Triangle Park (RTP) (see Table 1). For three of the sites, available satellite data covered the period from July 1996 until February 2000. For the Gaithersburg site Brewer DUV data are presented from July 1996 until October 2000. Necessary corrections to the raw data have now been implemented to address known instrument errors; these include (1) stray light rejection, (2) the cosine errors associated with the full sky diffuser, (3) the temperature dependence of the response of

the instruments and (4) the temporal variation in the instrument response due to changes in the optical characteristics of the instruments.

[8] In section 2 the instruments and methodology are described for the Brewer, the model and the satellite retrieval. The purpose of including the model is to provide a check on the new method for identifying clear-sky days, described in section 3, and as an aid in characterizing local conditions. Differences between the model and ground-based measurements provide information on these local conditions as the input parameters for the model are reflected in them. In section 3 the corrections to the Brewer are described (with details in the Appendix A). Comparisons of both the uncorrected and corrected data to a clear-sky model and to TOMS-inferred DUV data are described. A new methodology is presented for identifying clear-sky days. Using this method to select clear days, the relationship between the measured Brewer data and the model and between the measured Brewer data and satellite estimates of DUV are described. Finally, in section 4 the conclusions are outlined.

2. Instrumentation and Methodology

2.1. Brewer Spectroradiometer

[9] Brewer instruments use a quartz dome and Teflon diffuser with a hemispherical field of view to measure the spectral UV irradiance from which the DUV is derived. For the U.S. Environmental Protection Agency/University of Georgia (U.S. EPA/UGA) network, a dynamic schedule is used by the Brewer to maximize the number of UV readings/scans (with each scan taking approximately 6 min), to be recorded throughout the day, approximately every 30 min, and to ensure that a UV scan coincides with solar noon. The Brewer has a UV spectral range of 286.5–363 nm in 0.5 nm steps with an approximate resolution of 0.5 nm. UV irradiance calibrations, using a secondary standard lamp traceable to a National Institute of Standards and Technology (NIST) 1000 W lamp, are performed at the sites by staff of the National UV Monitoring Center (NUVMC), located at UGA. Resulting response functions were used to calculate irradiance from photon counts. Calibrations are targeted to occur once per year. In addition independent quality assurance audits of the instruments take place by the staff of the Central UV Calibration Facility of the National Oceanic and Atmospheric Administration (NOAA). To derive the DUV, the irradiance is first spectrally weighted with the erythemal response function and then integrated over the entire day.

[10] The Brewer instruments are also programmed to measure the total column ozone values from direct Sun (DS) scans; alternating with the spectral UV scans described in this paper. These ozone values were used as input to the UV model described later. The methodology of *Sabburg et al.* [2000] was used to correct the majority of ozone values to an uncertainty of less than ±3% in the ozone.

2.2. Corrections to Brewer UV Data

[11] *Bernhard and Seckmeyer* [1999] describe in detail the general principles of calculating the uncertainties of spectral solar UV irradiance. Many of these principles have been adopted in this present study and are listed in Appendix A, including references to other papers whose methods were also used. Brewer data were corrected for dark count, dead time and stray light using the algorithms of *Sci-Tec* [1999]. The action spectrum by *McKinlay and Diffey* [1987]—adopted by International Commission on Illumination (CIE)—was used to compute the erythemally weighted irradiance. The derivation of erythemally weighted UV irradiance from the spectral Brewer measurements requires a weighted UVA correction, where UVA is defined as UVR with the wavelength range of 320 to 400 nm. The UVA weighting was necessary because the wavelength range of the Brewer MKIV does not extend over the full UVA range, but rather stops at an upper limit of 363 nm. Instead, the correction is based on modeling the spectrum between 363 and 400 nm and weighting the irradiance at 356.5 nm [*Sci-Tec*, 1999]. Kerr (personal communication, 2001) explains that the error using the 356.5 nm wavelength is significantly less (by a factor of at least 5), than the error of 1–2% that is introduced by the method used by *Fioletov et al.* [2001] that uses a weighting at 324 nm. Kerr explains that the first order approximation is proportional to the irradiance between 325 and 400 nm and it follows that the 324 nm irradiance is also proportional to the CIE weighted integral for this range.

[12] The uncorrected and corrected data were converted to irradiance using available response functions as described in Appendix A.4. Additionally, the fully corrected data contained corrections for stray light, cosine response and temperature dependence. Quality checks have been performed on all data, e.g., removing extreme "outliers" due to electrical interference and faulty date assignment resulting from incorrect time stamps due to occasional computer clock malfunctions.

2.3. Model UV Data

[13] To estimate the UVR at each site, a two-stream radiative transfer model, TUVSPEC [*Kylling*, 1995] was used with Brewer ozone data as input, assuming cloudless skies with normal visibilities for each station (Table 1). The resulting time series is referred to as a modeled clear-sky envelope. The solar spectrum was based on SUSIM data from the Atlas-3 mission [*Van Hoosier*, 1996]. Calculations were performed using a 1 nm step over a wavelength range of 280 to 400 nm. A short term intercomparison was performed to compare each scan of corrected UV data from Brewer measurements at Boulder with modeled UV data for one clear-sky day for which detailed AOD measurements were available [*Estupiñán et al.*, 2001]. The modeled UV data were calculated using detailed AOD at 340 nm and ozone measurements with approximately half hourly resolution for 13 August 1999. The albedo in the model was set to 2%. Although the data set was not exhaustive, the comparison showed an agreement within a range of −5 to 12% for the SZA range of 25 to 50°. The DUV value agreed to within 5%, with the TUVSPEC value slightly larger than the Brewer value.

[14] For the long-term intercomparison study, the DUV was modeled with constant visibilities typically found at each site (Table 1), because long-term aerosol optical depth (AOD) measurements were not available. For RTP the typical visibility is 16.1 km (10 mi), for Gaithersburg it is 17 km, for Boulder and Rocky Mt. a value of 64.4 km was used. The aerosol parameterization in TUVSPEC is based on the work of *Shettle* [1989] with seasonally dependent aerosol profiles, which are scaled according to visibility. Table 1 lists the

Table 2. Percentage Differences, (Uncorrected − Corrected) * 100/Corrected, for Each UV Correction and All Corrections Applied to the Erythemally Weighted UVR Corresponding to One Scan Measured at Around Local Noon (SZA Shown in Table) on the 30 May 1999[a]

	Boulder	Rocky Mt.	Gaithersburg	RTP
SZA°/correction	18.5	18.5	17.5	14.3
Stray light	2.2	2.5	5.4	2.1
Cosine	−5.7	−11.1	−11.6	−9.5
Temperature	−8.3	0.4	−2.4	−3.2
Temporal	−6.2	0.4	−9.3	−16.4
All corrections	−18.4	−8.1	−17.0	−22.8
% DUV range for all corrections	−19.0 to 14.1	−12.7 to 5.7	−23.5 to −4.4	−29.6 to 5.1

[a]Percentage differences for fully corrected DUV values for all available data are also shown.

modeled AOD based on the site visibilities and elevations. The AOD varies from 0.05 to 0.12 at the high-elevated sites and the values are considerably less than the range of 0.67 to 0.72 used at the sites with low elevation. For calculating DUV, TUVSPEC was run in half hourly steps with ozone held constant during the day. For days with missing ozone data an interpolated ozone value was used.

2.4. UVR Inferred from TOMS Satellite Measurements

[15] Finally, a comparison is made with the inferred DUV data from the NASA TOMS instrument. The orbit of the satellite carrying the TOMS instrument allows an overpass time of approximately 1115 AM local time each day, with a corresponding footprint of approximately 40 km × 40 km. This footprint implies that the data measured by TOMS will be indicative of the atmospheric conditions over this spatial region. The TOMS DUV is calculated with a radiative transfer model. *Herman et al.* [1999] explains this model in further detail. The TOMS algorithm uses ozone data as well as reflectivity measurements at 360 nm to identify cloudy scenes. The daily integration is carried out assuming no diurnal variation in cloudiness, thus increasing the likelihood of making an error in estimating the DUV if cloud conditions change for other times of the day.

3. Results and Discussion

3.1. Stray Light, Cosine, Temperature, and Temporal Response Corrections to Brewer Data

[16] The procedures for implementing the corrections are outlined in the sections of the Appendix A. To provide an estimation of the relative contributions of the different corrections, Table 2 lists the percentage differences for each UV correction with respect to the corresponding uncorrected data. These corrections correspond to the erythemally weighted UVR of the scan at each of the sites measured at around local noon on 30 May 1999. In addition, this table lists on the bottom row the range of percentage differences for fully corrected DUV values for the whole data set. In this part of the table, most often the corrections are negative, indicating that the uncorrected data underestimated the actual DUV. However, there were a few positive values for Boulder and Rocky Mt. due to extremely low temperatures recorded during the UV measurement process. For example, at Boulder on 12 January 1997, the PMT temperature of the Brewer ranged from −16 to −10°C, which was quite unusual and probably resulted from an internal heater problem. It was also found that a few positive values for the RTP site were due to unusually excessive values of stray light entering the PMT.

[17] An analysis of the uncertainty in the corrections is presented in Table 3. The first two rows of the table indicate the dependence of the response on temperature, expressed as percent per °C and the annual average change in response, both specified at 310 nm. The wavelength of 310 nm typically makes the greatest contribution to the erythemally weighted dose. The next six rows show the estimated uncertainty for the various factors that determine the correction. Many of these are identical for all Brewers such as the uncertainty in the calibration lamp irradiance, and the uncertainty of the transfer of this irradiance to the Brewer during calibration. However, the uncertainty of the

Table 3. Parameters Used in the Corrections for Each Brewer (rows 1 and 2) and an Analysis of the Error Budget

		Boulder	Rocky Mt.	Gaithersburg	RTP
Temperature coefficient at 310 nm (%/°C)		−0.5	−0.17	−0.16	−0.25
Average annual change in response at 310 nm		−10%	<1%	−14%	−14%
Correction uncertainty	Stray light	≪1%	≪1%	≪1%	≪1%
Correction uncertainty	Calibration lamp	±2%	±2%	±2%	±2%
Correction uncertainty	Calibration transfer	±2%	±2%	±2%	±2%
Correction uncertainty	Cosine	±2%	±2%	±2%	±2%
Correction uncertainty	Temperature	±4%	±1.5%	±1.5%	±2%
Correction uncertainty	Temporal interpolation of response	±3%	<1%	±4%	±4%
Correction uncertainty	Total (RMS)	±6%	±4%	±5.5%	±6%

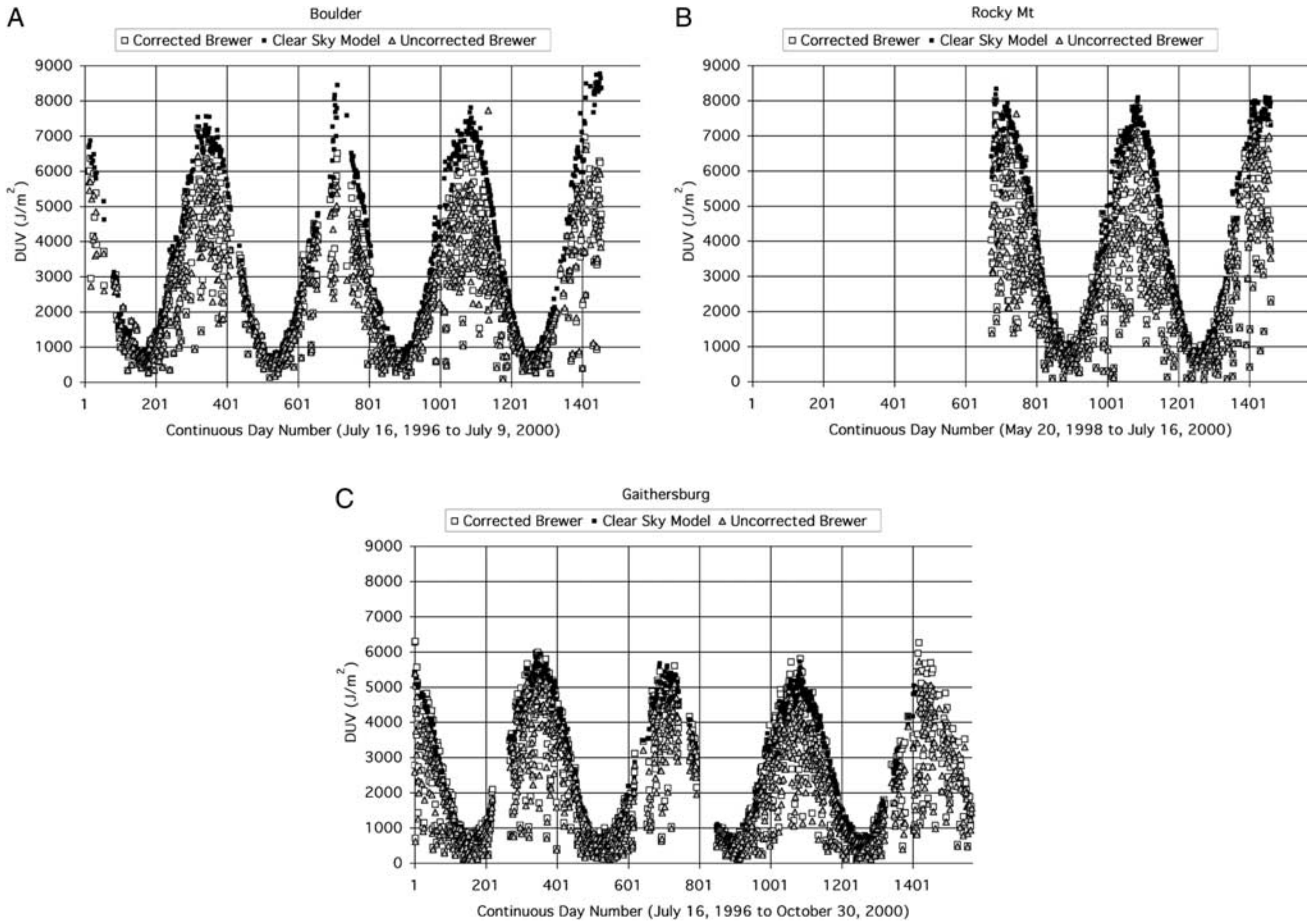

Figure 1. Graphs showing all available uncorrected and corrected DUV levels for Brewer (a) 101 (Boulder), (b) 146 (Rocky Mt.), (c) 105 (Gaithersburg), and (d) 087 (RTP) compared to the corresponding clear-sky modeled data for the dates as shown on the x-axes.

corrections due to (1) the deviation of the diffuser from a perfect cosine response, (2) the temperature dependence of the response and (3) the linear interpolation of the response between calibrations depend on the particular instrument. The cosine correction is similar for these four Brewers and its uncertainty is estimated at ±2%. The uncertainty in the temperature correction is estimated assuming a 30% uncertainty in the temperature coefficients and a 25°C temperature change of the instrument during measurement with respect to the temperature of calibration. It is an upper limit that applies to the most extreme end of the range of temperatures. It is proportional to the temperature coefficient of the response. The uncertainty resulting from the assumption of a linear interpolation of the response between calibrations is estimated at about 30% of the average annual change in response. The result of this error budget is that for these four instruments, the RMS uncertainties to the correction lie in range of 4–6% (including the uncertainty of the 1000W lamp calibration), with the Rocky Mt. instrument showing the smallest uncertainty, due mainly to the stability of its temporal response. These estimated errors refer to the UV irradiance at each wavelength in each scan. While the errors in the daily doses can be expected to be less, to the extent that some of the errors get averaged over the day, these error estimates will be assumed for the daily doses in the analysis of the results.

3.2. Comparison Between Uncorrected and Corrected Brewer With Clear-Sky Modeled DUV Data

[18] As this is the first time that fully corrected UV data has been published from this UV network, it is important to present (Figure 1) a time series graph of the uncorrected, and corrected Brewer results along with the results of the clear-sky TUVSPEC model DUV data for all available data at (a) Boulder, (b) Rocky Mt., (c) Gaithersburg and (d) RTP sites. Such a comparison indicates the magnitude of the corrections and its variation from day to day and with season. In addition, a time series comparison to clear-sky modeled results provides a rough test of the appropriateness of the local atmospheric parameters that were chosen in the model for the four sites. As the Brewers used a dynamic schedule, the number of expected UV scans varied from approximately 15 to 35, dependent on day number and site latitude. On some occasions, due to technical problems, an incomplete number of scans resulted. Only Brewer data corresponding to a complete full day of UV scans are presented. Modeled data are shown for days on which the difference between TOMS and Brewer ozone values were less than 10%. At all sites, the corrections bring the

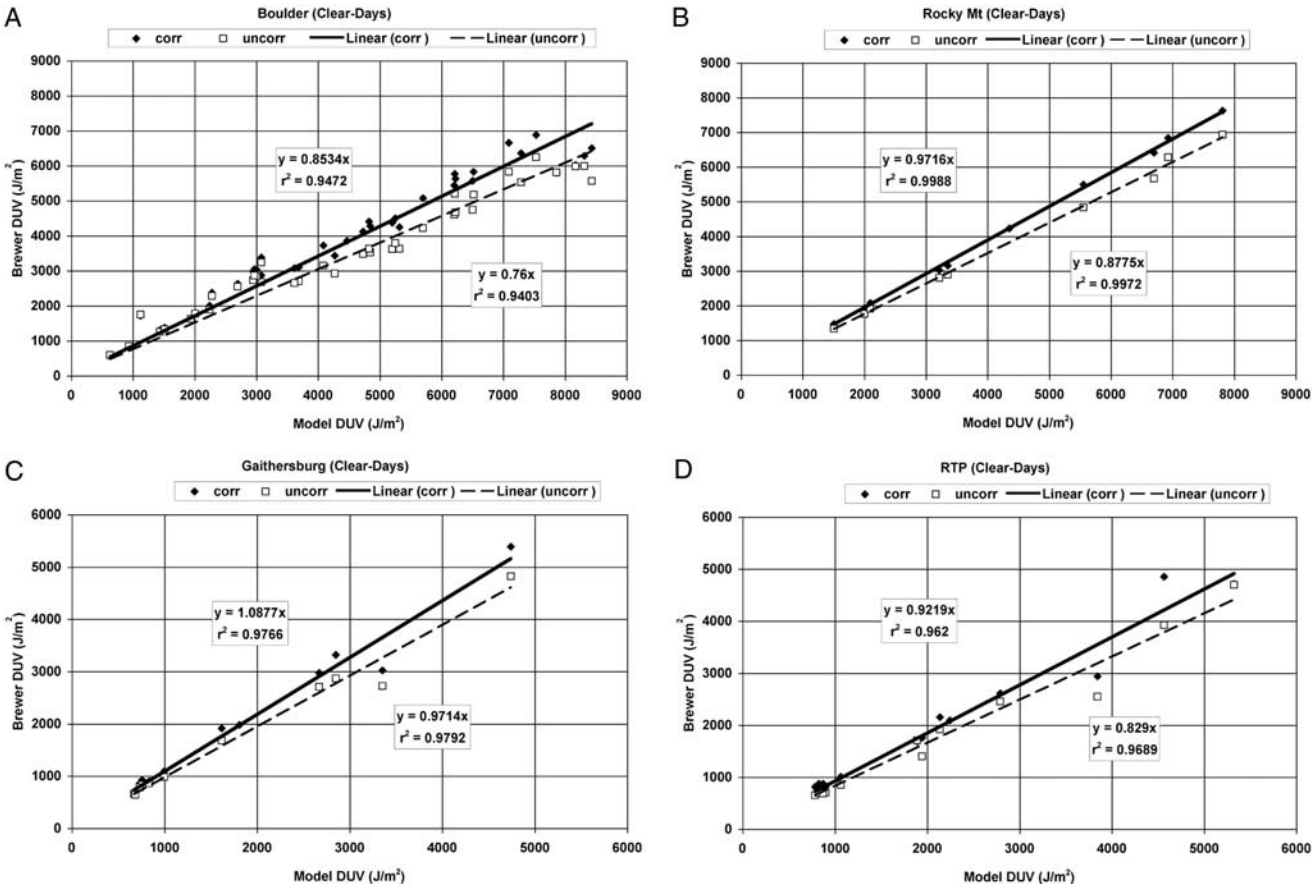

Figure 2. Correlation graphs of corrected and uncorrected Brewer DUV data versus clear-sky model data for days determined to be clear-sky (a) Boulder, (b) Rocky Mt, (c) Gaithersburg, and (d) RTP. Linear correlation coefficients, slope, and intercepts are also shown.

measured DUV in closer agreement with the clear-sky modeled envelope. For the Gaithersburg site, the corrected values exceed the model envelope on a number of days by an amount that is larger than the estimated uncertainty of the measurements.

[19] Figure 2 compares the clear-sky DUV values measured by the Brewer with values calculated for TUVSPEC and shows linear correlation coefficients, slope and intercepts of the uncorrected and corrected clear-sky DUV versus the corresponding values calculated from TUVSPEC. A new method of determining clear skies (cloudless skies) was used for producing the data in this figure (J. Sabburg et al., New methods for determining "clear" skies using a Brewer spectrophotometer, submitted to *Journal of Atmospheric and Oceanic Technology*, 2002, hereafter referred to as Sabburg et al., submitted manuscript, 2002). Unlike other methods that use the ratio of measured to modeled UV values, or just use TOMS reflectivity data alone, this method uses a combination of the standard deviation of DS scans (selected UV wavelengths used for direct Sun ozone measurements) and TOMS reflectivity data. DS scans are made in rapid succession of one another, thus enabling the determination of any sudden changes in the presence of cloud. This minimizes the number of days that would have been misidentified as completely clear-days if using TOMS reflectivity data alone. For example, TOMS overpass data is recorded at approximately 11:15 AM local time and cannot take diurnal cloud variation into account. Also, TOMS reflectivity data can be effected by high surrounding terrain, as found in the Rocky Mt. site, and by the presence of snow that can be mistaken as cloud cover. The method has been tested using an in situ sky-camera and the resulting algorithm that was used for classifying clear days in this paper is:

$$\text{Clear Day} \equiv (A > 95\% \text{ AND } B > 70\% \text{ AND } C < 2\%) \quad (1)$$

where (A) is the number of "measured"/ideal number of DS scans for that day (where "measured" are DS scans not aborted due to a cloud moving across the Sun), (B) is the number of "good"/the number of measured DS scans (where "good" is defined as those scans having a standard deviation <2.5 DU) and (C) is the TOMS reflectivity.

[20] This resulted in a total of 41 completely clear days at Boulder (4% of available data), 9 for Rocky Mt. (1.2%), 11 for Gaithersburg (0.9%) and 12 for RTP (1.1%). As expected the clear-sky corrected data show a greater slope than that of the uncorrected data for all sites. For all sites except Gaithersburg, this brings the measured DUV into closer agreement with the model clear-sky values than was the case for the uncorrected data. In the case of Gaithersburg, the slope for the corrected data is actually slightly

Table 4. Percentage Deviation of Clear-Sky, Corrected DUV Values at Four Sites With Values Predicted With the TUVSPEC Model and Those Values Inferred From TOMS Measurements[a]

Site	Average bias, % (Brewer − TUVSPEC) * 100/TUVSPEC	Slope of clear-sky correlation graphs (Brewer DUV data versus model)	Average bias, % (Brewer − TOMS) * 100/TOMS	Slope of clear-sky correlation graphs (Brewer DUV data versus TOMS)
Boulder	−13.9	0.853	−2.5	0.926
Rocky Mt.	−3.1	0.972	−1.4	0.990
Gaithersburg	9	1.088	−3.0	0.986
RTP	−7.1	0.922	−12.5	0.912

[a]The slopes corresponding to Figure 3 are also presented.

greater than 1. No significant change in the correlation coefficients between the plots of uncorrected and corrected data is observed for the four sites.

[21] Table 4 (column 1) summarizes the average clear-sky differences between the corrected Brewer and modeled data, (corrected − model) * 100/model and in column 2 the slopes of the graphs of the correlation between measured and modeled DUV values are tabulated. For example, the range of deviation of the DUV values for Boulder was −26.4 to 9.6% with an average difference of −13.9% and the slope of the correlation graph was 0.853. For three of the sites the average differences between the measured and modeled DUV values are less than 9% and fall almost within the ±6% uncertainty of the measurements. For the Rocky Mt. site, that has the lowest estimated uncertainty, the difference in the slope of the correlation plot is about 3%. However, for the Boulder site the difference is almost 15%, which suggests that the local atmospheric parameters that were input into the model were in error. The most likely of these is the AOD values, whose seasonal average values of 0.12 (Spring–Summer) and 0.08 (Fall–Winter) may need to be revised upward. Similar adjustments of the AOD values for Gaithersburg and RTP could bring the clear-sky model and measured DUV values into better agreement but since the slopes of the differences between the model and measured values fall just outside the uncertainties of the measured values, such an adjustment would not be justified.

3.3. Comparison Between Corrected Brewer and TOMS-Derived DUV Data for Clear Skies

[22] Before a comparison with TOMS data was undertaken, the TOMS values for both Boulder and Rocky Mt. were adjusted for altitude. Results from site-specific TUVSPEC calculations showed that DUV increases, annually averaged, by 21 J/m_2 per 100 m increase in altitude under clear-sky conditions when the total ozone is 300 DU (see Table 1 for altitude differences and aerosol conditions). The actual correction value depends on the actual ozone amount and the day of year. These variations have been taken into account when performing the correction. For example, the TOMS-inferred DUV at Rocky Mt., where the difference between overpass altitude and station elevation was 1.5 km was increased from the overpass value by 9.3% on average due to the altitude correction. After these corrections, the average difference between the corrected clear-sky Brewer DUV values for the two sites of Boulder and Rocky Mt. (over 1 km difference in altitude and 20 km in proximity), for overlapping days was +15.8%, (Rocky − Boulder) * 100/Boulder. This represents an increase of 15.8% of the average of all overlapping DUV data for Rocky Mt. compared to Boulder. If the altitude were the major difference for these two sites that are in close proximity, one would expect this difference to be reflected in the measured values as well. Indeed it is close to the measured difference between the two sites of 6.5% that falls within the expected agreement based on the uncertainties in the measured DUV values at the two sites of ±6% (Boulder) and ±4% (Rocky Mt.).

[23] Figure 3 compares the clear-sky DUV values measured by the Brewer with corresponding values inferred from TOMS along with linear correlation coefficients, slopes and intercepts. Once again, the method of Sabburg et al. (submitted manuscript, 2002) was used for determining completely clear-sky days. Table 4 (columns 3 and 4) summarizes the average clear-sky differences between the corrected Brewer and TOMS DUV values, (corrected − TOMS) * 100/TOMS, as well as the slopes of the lines of best fit. For all of the sites, the TOMS-inferred slopes show a positive bias. For two of the sites (Rocky Mt. and Gaithersburg) the differences between the slopes of the correlation of the measured and TOMS-inferred DUV values are only about 1% and the differences between the average DUV values is within 3%. For the other two sites (Boulder and RTP) the slopes indicate a difference of only 7% and 9%. Since these differences are not far outside the 6% uncertainties of the measurements this indicates a relatively very good agreement for all four sites.

4. Conclusions and Future Research

[24] When UVR measurements with a MKIV Brewer spectrophotometer are corrected for the temperature dependent response, temporal variation of response, stray light and the angular dependence of the collector, the uncertainty of absolute irradiance is estimated to be in the range of ±4 to ±6% (depending on site) for all known major sources of error. This estimate is similar to the uncertainty value of 6.1% as calculated by *Bernhard and Seckmeyer* [1999] for erythemal UV associated with their particular spectral instrument.

[25] Corrections to the DUV values for the complete data set at the four sites studied change the uncorrected values in the range of 30 to −14% (see Table 2). Corrected DUV values on clear-sky days fall in much closer agreement with modeled DUV values than those of the uncorrected data. The average differences between clear-sky model or TOMS-inferred DUV values with respect to the corrected

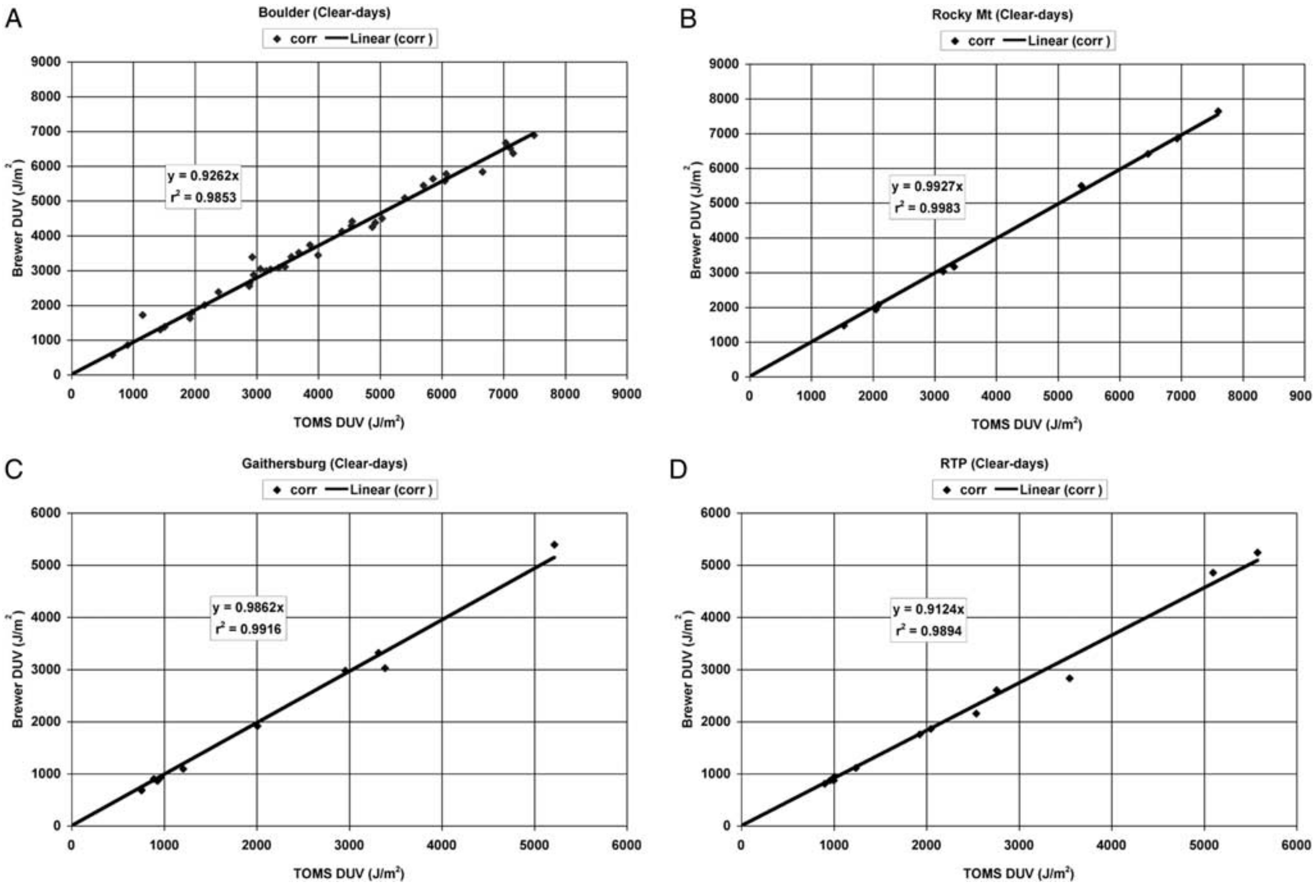

Figure 3. Correlation graphs of corrected Brewer DUV data versus TOMS data for days determined to be clear-sky (a) Boulder, (b) Rocky Mt, (c) Gaithersburg, and (d) RTP. Linear correlation coefficients, slope, and intercepts are also shown.

Brewer DUV values for the four sites were in the range of 14 to −9% and 12.5–1.4%, respectively. The smallest average value difference of −3.1% (compared to model) and −1.4% (compared to TOMS) both corresponded to the Rocky Mt. site, and in the case of TOMS, this is the lowest value quoted in the literature at this time. The average bias for all four sites is 5% with the TOMS-inferred values being greater.

[26] In the recent study by *McKenzie et al.* [2001], positive biases of 17% (Toronto), 25% (Thessaloniki), and 38% (Garmisch-Partenkirchen) where observed for the three northern hemisphere sites. Only for the pristine southern hemisphere site at Lauder, NZ was the bias small (−2%). They concluded that the ±12% stated accuracy of satellite retrievals of DUV is overly optimistic. The results of the present study suggest that this may not be the case in general and that at least under clear-sky conditions; the stated ±12% estimate of accuracy may be appropriate. For all four sites, the slopes of the correlation between measured and satellite-retrieved DUV values are in agreement considering the uncertainties of the ground and satellite results. There are a number of reasons why the observed biases may have been greater in the previous study [*McKenzie et al.*, 2001]. Their data set included data from days under all atmospheric conditions. In addition their ground-based measurements assumed a constant 6% cosine correction and, at least for some of the sites, did not include a correction for the temperature dependence of the instrument response.

[27] An evaluation of the TOMS-inferred values of surface irradiance that can provide a validation of these estimates will require the most accurate ground-based measurements. Future research in the UGA/U.S. EPA network will include a refinement of the correction of the Brewer UV data further reducing the estimated errors. Reanalysis of this data, and similar corrections applied to the remaining 17 sites, will produce an extensive full spectral UV data with an estimated accuracy of better than 6%. This data set will encompass a wide range of latitudes and local atmospheric conditions and will provide the UV community with an extensive additional spectral UV database to that which is currently available that can be used to validate the satellite retrievals of UVR.

Appendix A

A.1. Stray Light Rejection

[28] Stray light relates to photons of light measured by the Brewer that is not intended to pass into the Brewer's monochromator. Although stray light is independent of the nominal wavelength setting of a monochromator, *Sci-Tec* [1999] suggests that the number of photons corresponding to the first twelve wavelengths scanned by the Brewer approximates this stray light. Thus, for each of the dark

and dead-time corrected count rates (DC) corresponding to the 154 wavelengths (286.5 to 363.0 nm) per UV scan of the Brewer, the average DC of the first twelve wavelengths is subtracted from each DC of the 154 wavelengths in question to provide the first approximation for this stray light corrected (SC) data.

A.2. Cosine Correction

[29] *Sabburg and Meltzer* [2000] explain the cosine correction methodology associated with the full sky diffuser in detail. In summary, cosine response measurements were made on each Brewer using the irradiance of a standard 1000 W lamp. These measurements were performed in the laboratory. The final values were based on an average of measurements along the long and short sides of the Brewer. Data was obtained for five wavelengths (306.3, 310.1, 313.5, 316.8 and 320.1 nm) that were averaged along with the results of two sets of zenith angle ranges (-80 to $0°$ and $0°$ to $80°$ in $10°$ steps).

[30] The equations of *Bais et al.* [1998] were used to calculate the total cosine correction assuming a diffuse isotropic clear-sky. The ratio of the direct/global irradiance was based on the clear-sky model of *Rundel* [1986]. This model data was used as the direct Sun port was not calibrated, thus preventing a measurement of the ratio of the direct/global. The ozone input was based on corrected ozone amounts from the Brewer and if not available a nominal value of 300 DU was used. The aerosol optical depths (AOD) were based on the typical visibility for each site. An average of the Spring–Summer and Fall–Winter values (Table 1) was used.

A.3. Temperature Dependence

[31] The Brewer temperature fluctuates with the ambient at the various locations from approximately 0 to + 50°C. There is a significant wavelength dependence of the temperature coefficient below 325 nm. This is primarily due to the temperature dependence of the transmission of the nickel sulfate filter.

[32] Staff of the NUVMC, during a field campaign in July 2000, measured the temperature dependence of two of the Brewers (101 and 146). Staff at RTP measured the temperature dependence of Brewer 087 during November 2000. The methodology for measuring the temperature dependence of these three Brewers is outlined by *Meltzer et al.* [2000]. Basically, the methodology utilizes spectra of 50 W Brewer calibration lamps recorded throughout one day during the diurnal temperature cycle. These measurements utilize more accurate and more stable current and voltage monitoring equipment for control of the 50 W lamp output than is supplied with each Brewer. Plots of the photon counts versus temperature at each wavelength are used to determine a temperature coefficient, $\Delta R/\Delta T$, which is the slope of the response versus temperature.

[33] In the case of Br 105, no field campaign had been undertaken by the NUVMC; instead, the results of *Weatherhead et al.* [2001] using the available 50 W lamp scan data over a number of years, was utilized to obtain the temperature coefficients. The temperature corrections were achieved by normalizing photon counts of each scan to an equivalent photomultiplier tube (PMT) temperature of 20°C, using the derived temperature coefficients.

A.4. Temporal Variation

[34] The temporal variation in the instrument response is due to changes in the optical characteristics of the instruments. This necessitates an annual UV irradiance calibration at the site performed by NUVMC staff, using a secondary standard lamp traceable to the NIST 1000 W lamp. This results in response functions that are used to calculate irradiance from photon counts and typically a linear interpolation is applied to the response function between calibrations for the fully corrected data. Uncorrected data utilizes the most recent instrument response function that, for some days, can be a year or more earlier. Since the response usually decreases with time, the temporal correction is almost always positive. In addition, staff of NOAA, using similar equipment to that of the NUVMC, conducts independent quality assurance (QA) audits of the instruments. Details of these procedures are available at the Web address: ftp://oz.physast.uga.edu/Outgoing/ by downloading the three documents entitled: "SOP1_FEL-Lamp.doc," "SOP for Field Calibration.doc" and "Irradiance Transfer of 1000 Watt lamps.doc." One of the instruments, Brewer 101, took part in a UV intercomparison at Boulder during 1997. It was shown that during synchronized solar irradiance measurements all spectral instruments participating in the intercomparison had a relative standard deviation of ±4% for wavelengths greater than 305 nm [*Lantz et. al.*, 2000].

[35] **Acknowledgments.** The authors would like to thank U.S. EPA project officers Jack Shreffler and Tom Lumpkin (also the RTP operator), the site operators at Boulder, Rocky Mt., and Gaithersburg, the NASA/Goddard Space Flight Center via Edward Celarier (Software Corporation of America) for the Level 1 TOMS DUV data, Jeral Estupiñán for advice on aerosol optical depth values, and Dave Theisen of NOAA for supplying the temperature coefficients for Gaithersburg. This paper is dedicated to P. M. Udelhofen.

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