Comparison of ultraviolet data from colocated instruments from the U.S. EPA Brewer Spectrophotometer Network and the U.S. Department of Agriculture UV-B Monitoring and Research Program

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Abstract. Several ground-based ultraviolet (UV) monitoring networks exist in the United States, each of which is unique in the instrumentation employed for measurements. Two of these UV networks are the U.S. Environmental Protection Agency's (EPA's) Brewer Spectrophotometer Network and the U.S. Department of Agriculture's (USDA's) UV-B monitoring network, with a combined instrument total of 52 sites, with 32 sites located in the mainland United States. The Brewer records full sky spectra from 287 to 363 nm with 0.55-nm resolution, whereas the USDA instrument is a broadband device that measures broadband erythemally weighted UV data. To date, limited comparisons of data collected from these networks have been analyzed for comparative and quality assurance (QA) purposes. The data we use is taken from sites where instruments from each program are colocated, namely, Big Bend National Park, Texas, and Everglades National Park, Florida. To reduce the contribution of errors in the Brewer-based instruments, the raw data is corrected for stray light rejection, the angular response of the full sky diffuser, the temperature dependence of the instruments, and the temporal variation. This reduces the estimated errors of the absolute irradiance values of each Brewer spectral measurement to approximately ±5%. The estimated uncertainty of the USDA instruments is approximately ±6% with a systematic bias of (−13 to 5% depending on the total ozone) and is comprised of (1) standard lamp measurement errors, (2) spectral response determination, and (3) the angular response of the diffuser. We perform comparisons between the Brewer spectrally integrated and erythemally weighted UV irradiance measurements and the data collected by the broadband erythemal UV meters at colocated sites between 1997 through to 2002. [DOI: 10.1117/1.1885470]

Subject terms: ultraviolet monitoring networks; spectral measurement; irradiance.

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1 Introduction

Natural protection from harmful solar UV-B radiation provided by the atmosphere has declined over the past 2 decades with decreasing stratospheric ozone levels, due to anthropogenic emissions of ozone depleting substances.[1] An inverse exponential relationship exists between biologically damaging UV radiation and stratospheric ozone concentration,[2] and also between the incidence of skin cancer and UV-B irradiance.[3] The downward trend in stratospheric ozone over this period has therefore raised concerns about the levels of biologically damaging radiation encountered at the earth's surface and its effect on human health. In response, the demand for cost and labor effective UV quantification methods has increased.

To assess long-term changes in the surface levels of solar UV radiation, careful long-term UV data sets over varied climatological areas must be acquired. The two largest networks collecting spectrally resolved UV data are the Environmental Protection Agency (EPA) network utilizing Brewer spectroradiometers at 21 sites over the United States and the U.S. Department of Agriculture (USDA) network using broadband instruments at 32 sites across the United States. Two of the instruments in each network are colocated, offering the opportunity to compare the irradiance measurements of the two networks at two sites over an extended period of time. Such a comparison enables a com-

Table 1 Uncertainty estimate for clear-sky daily dose of erythema from YES-UVB radiometers at Big Bend, Texas and Everglades, Florida.

Uncertainty Source	Comments	Uncertainty Contribution	
		Random	Systematic
Spectroradiometer		±5%	
Transfer from triad		±1%	
Angular response (AR)	Contribution of differences in AR to error	±3%	
Spectral response (SR)	Contribution of difference in SR to error	±1%	
Ozone	Contribution of error to daily dose		200 DU: −13%
			300 DU: 0%
			400 DU: +5%
Temperature		±0.1%	
Total		±6%	−13 to +5%

parison of the relative absolute calibrations of the instruments, their relative stability with time, and potential sources of residual error in the resulting data.

2 Instrumentation and Methodology

2.1 *Ground-Based Instruments*

2.1.1 *University of Georgia (UGA)/EPA Brewer spectroradiometer and data correction*

The UV irradiance measurements were obtained using MkIV Brewer instruments in the UGA/EPA Brewer network that record spectra in 0.55-nm steps over the UV spectral range of 286.5 to 363 nm. From this point forward in the paper, these instruments are referred to as UGA/EPA. 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 UGA's National UV Monitoring Center (NUVMC) approximately once per year. The fully corrected Brewer data uses an estimated daily temporal response based on the annual UV irradiance calibration. Additionally, independent quality assurance audits of the instruments take place by staff of the National Oceanic and Atmospheric Administration (NOAA).

Regular (quarterly) checks on transfer of the calibration from the NIST 1000-W lamp to the traveling secondary standard were performed at the NUVMC. The response function of each instrument is calculated for each day based on a linear interpolation between the two temporally closest response functions. The temporal corrections typically increase the UV irradiance relative to that of the uncorrected data, which assumes the last response, since usually the instrument response decreases with time such that the actual response is less than that assumed based simply on the last calibration. Brewer data were corrected for dark count, dead time, and stray light using the algorithms of Sci-Tec.[4]

The data are then corrected for the instrument's cosine response and temperature dependence. Each instrument is characterized for the angular dependence of its response at 5-deg increments along two mutually perpendicular directions. A standard operating procedure (SOP) available at the UGA Website (http://oz.physast.uga.edu) describes this process. A correction is then applied under the assumption of a diffuse isotropic clear sky and a ratio of the direct/global irradiance based on a clear-sky model of Rundel.[5] The cosine correction leads to an increase in the UV irradiance relative to that of the uncorrected data since the full sky collector operates at a reduced throughput for rays at large angles from the zenith, the angle for which the instrument is calibrated. The wavelength-dependent temperature coefficient of each instrument has been characterized in the field using a specially stabilized 50-W Brewer calibration lamp, throughout 1 day during the diurnal temperature cycle. The wavelength dependent temperature coefficient is typically about −0.1 to −0.4% per degree centigrade, but it can be as large as 1% per degree centigrade in some wavelength ranges.[6] Temperature corrections to the deep UV (DUV) can be positive or negative, depending on the relative temperature of a UV scan to that of the temperature when the calibrations were performed.

2.1.2 *USDA broadband instrument*

The USDA's UV-B Monitoring Program's UV data set used in this research was derived from broadband UV sensors at two of their sites operating in the continental United States. The USDA's UV Network uses Yankee Environmental System (YES) UV-B1 broadband radiometers. A general overview of the design of this type of broadband radiometer is given in Berger et al.[7] From this point forward in this paper, these instruments will be referred to as USDA. Data is collected at each site in 3-min intervals throughout the course of the day. These sensors have the advantages of mechanical simplicity and a high measurement frequency, and the resulting data set enables detailed studies of the temporal behavior in UV irradiance. The limitation is that the broadband information alone does not enable unambiguous attribution of observed variability to a specific cause, such as a change in ozone or in cloudiness. Each broadband radiometer is characterized annually for spectral

Table 2 Measurement site parameters.

Site	Latitude	Longitude	Alt. (m)	Obstructions	Data Range
Big Bend Brewer	29.31 deg N	103.13 deg W	1131	Mountain obstruction to 15 deg, S	1997 to 2002
Everglades Brewer	25.39 deg N	80.68 deg W	0	Unobstructed	1997 to 2001
Big Bend USDA	29.13 deg N	103.52 deg W	670	Slight horizon obstruction by mountain	1997 to 2002
Everglades	25.38 deg N	80.68 deg W	0	Unobstructed	1997 to 2002

and cosine response. The absolute calibration of each USDA radiometer is performed annually by comparing the output of the broadband sensor in sunlight with that of three collocated YES UV-B1 standard radiometers (the CUCF triad) for 2 weeks. The CUCF triad is calibrated for erythema as a function of solar zenith angle (SZA) and total ozone in the field against a collocated precision spectroradiometer.[8]

The CUCF provides erythema calibration factors for the UVB broadbands as a function of SZA and total ozone, or as a function of SZA assuming a total ozone of 300 Dobson units. The latter erythema calibration factor is more convenient when total ozone is not available at each site and the larger resulting uncertainties are not a concern. The USDA provides erythema data with the SZA-dependent diffey-weighted erythemal calibration factors that assumes a total ozone value of 300 DU because this is often sufficient for the users in this community. The broadbands were judged especially stable against the triad with the median change in scale factor for 30 instruments of 0.5% with a standard deviation (SD) of 0.39%. The CUCF triad was first calibrated in 1994. Calibration results for the triad show that the triad has decreased in sensitivity by approximately 1.1%/year since 1994. The USDA instrument is temperature stabilized to 45±1°C. The broadband radiometers are calibrated by a spectroradiometer whose estimated uncertainty[9] is approximately ±5%; the combined uncertainty of broadband radiometers in general has been estimated at approximately ±10%.[10] An uncertainty estimate in the calculation of the daily erythema dose for clear-skies as used in this paper is given in Table 1. Cloudy sky conditions would result in larger uncertainties and can be seen in the comparison of spectral and broadband measurements under all-sky conditions.[11]

2.2 *Sites*

Two sites are included in this study, one located at Everglades National Park and the other at Big Bend National Park. The latitudes, longitudes, altitudes, site obstructions and data periods are summarized in Table 2. The instruments at the Everglades sites are located within a few hundred meters of one another and share an unobstructed sky view. The instruments at the Big Bend site are located in two different parts of the park separated by about 26 miles (40 km). The UGA/EPA instrument has mountain obstructions up to 15 deg from the horizon to the south.

2.3 *Clear-Sky Day Determination*

Clear-sky days, based on the UGA/EPA Brewer data, were identified using an algorithm utilizing the ratio of two sequential Brewer UV scans (typically 20 to 40 min apart). Ratios are obtained through integrating data over the UV waveband of the irradiance values of two successive scans. Only days that have UV increases during the first part of the day and decreases in the second part are to be labeled as clear sky days. During this comparison, the limits supplied

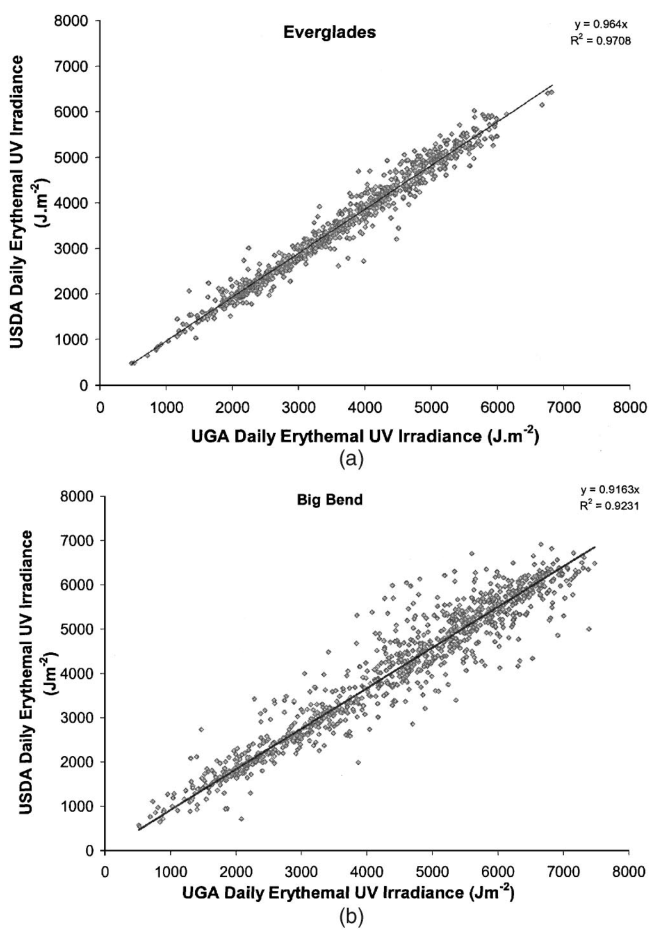

Fig. 1 Regression plots of the UGA/EPA Brewer spectrophotometer data versus the USDA broadband erythemal UV data for the (a) Everglades (Florida) and (b) Big Bend (Texas) colocated sites.

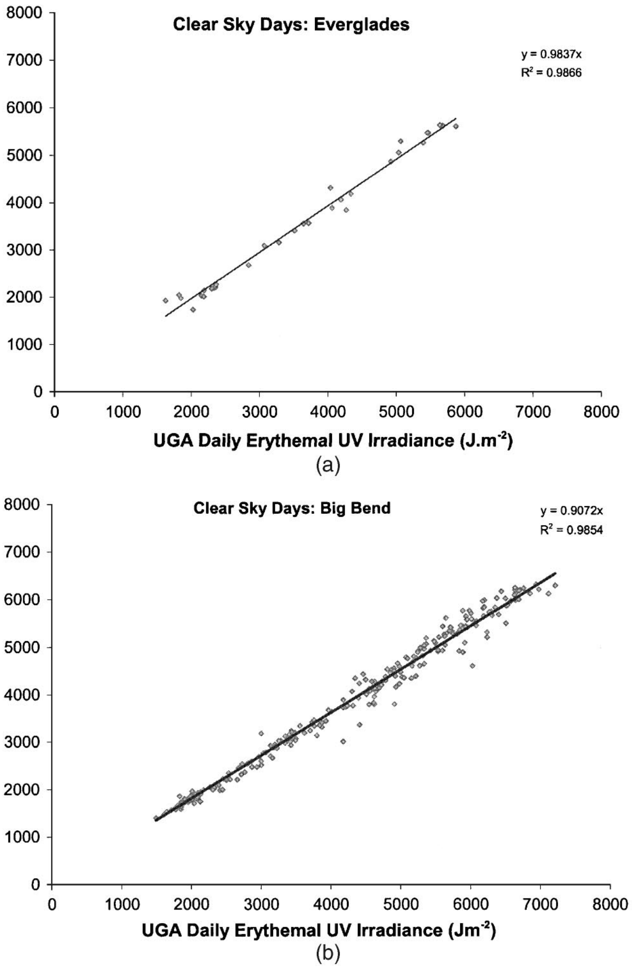

Fig. 2 CSD regression of the (a) Everglades data and (b) Big Bend data.

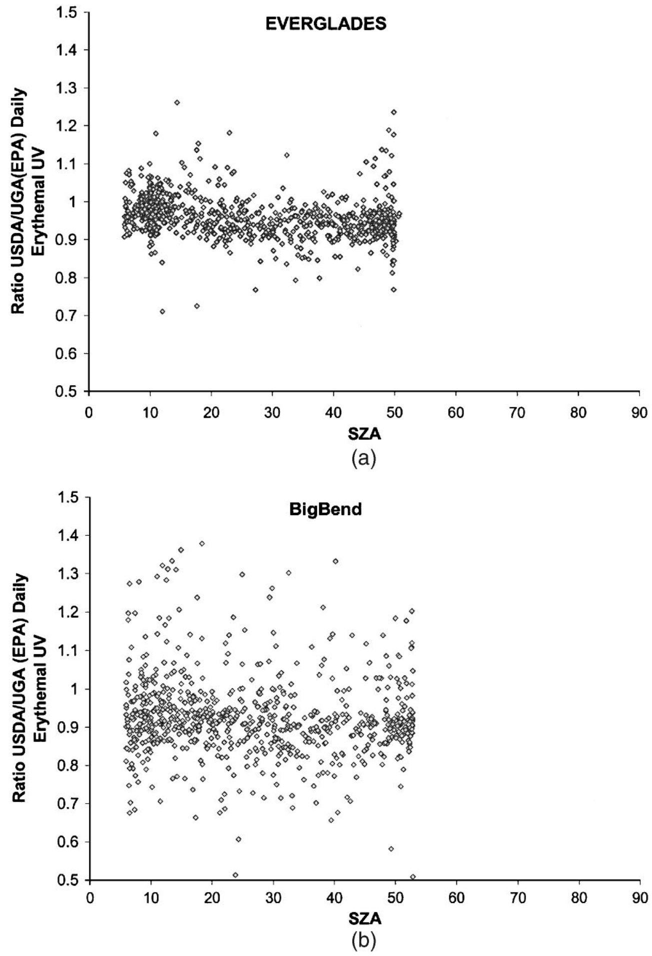

Fig. 3 Daily erythemal UV irradiances versus 1 pm (local time) SZA for (a) Everglades and (b) Big Bend.

by the user are used to limit the value of the ratio of successive scans. Clear-sky days were assumed to occur if this ratio fell within the range of 0.8 to 1.2 for all wavelength values for solar zenith angles +75 to −75 deg. Also, any day that has less than 15 scans is also not flagged as a clear sky day. While this clear-sky algorithm identifies days free of variable clouds they may still contain uniform thin clouds or aerosols. It is assumed that the clear sky day for the UGA/EPA site corresponds with a clear sky day for the USDA site.

2.4 *Satellite Data*

A comparison of the collected UV data is made with the total column ozone data collected from the National Aeronautics and Space Administration (NASA) total ozone mapping spectrometer (TOMS) earth probe instrument. The purpose of this investigation is to assess the impact of ozone the data collected from each instrument. TOMS ozone data is indicative at the time of overpass (about 11:15 am local time) and the footprint for the TOMS instrument is approximately 50×50 km at nadir and 100 ×100 km average.

3 Results

Data presented is the daily integrated erythemally weighted UV referred to hereafter as daily DUV. Prior to analyzing the data, quality checks on the data were carried out. USDA data and UGA/EPA Brewer data were initially rejected if less than 50 and 80%, respectively, of the expected UV scans for a particular day were not performed, as this may affect the integration of the data over the entire day. Data from the Brewer instrument was also rejected if random instrument data spikes were observed in the solar scans. Also omitted were days in which scans around solar noon were missing, or days for which scans started too late or ended too soon in the day, as this affects the way the daily integration of data is performed. For example, it is estimated that three to four missing scans around solar noon can affect the daily UV integration by ±5 to ±10%. In addition, individual days that had poor correlations between UGA/EPA and USDA were examined and rejected on a case by case basis. If the UGA/EPA data met all the criteria needed to be maintained as good data, then the USDA data was examined to determine the occurrence of missing scans. Several days (about 2 to 5%) from USDA's data were deleted due to missing data over significant portions of the day.

Table 3 Ratio of USDA broadband UVB data to EPA/UGA Brewer data (seasonal and annual averages).

	Big Bend, Texas	No. of data	Everglades, Florida	No. of data
Spring (all years)	0.923 (0.08)	278	0.981(0.06)	222
Summer (all years)	0.940 (0.10)	254	0.972(0.06)	230
Fall (all years)	0.914 (0.10)	233	0.937(0.05)	209
Winter (all years)	0.909 (0.10)	221	0.953(0.06)	169
1997	0.917 (0.10)	178		
1998	0.946 (0.11)	218	0.936(0.05)	172
1999	0.948 (0.07)	92	0.977(0.05)	207
2000	0.933 (0.07)	158	0.973(0.07)	163
2001	0.894 (0.09)	285	0.971(0.06)	270
2002	0.928 (0.10)	55	0.961(0.06)	21
SZA range 5 to 20 deg	0.931 (0.09)	311	0.981(0.06)	361
SZA range 35 to 50 deg	0.918 (0.10)	320	0.946(0.06)	280
Clear days	0.908 (0.06)	229	0.954(0.06)	42
All data	0.923 (0.10)	986	0.962(0.06)	833

Scatter plots of the relationship between the USDA and UGA/EPA daily DUV are shown in Fig. 1 for the Big Bend and Everglades sites. For the Everglades data, based on the slope of the linear best fit (forced through the origin) to the scatter plot, the broadband USDA instrument data was found to be, over the entire data collection period, 3.6% lower than the recorded data from the UGA/EPA instrument, with an R^2 value of 0.97. At the Big Bend site, the USDA data is 8.4% lower than the UGA/EPA data, with a lower R^2 value of 0.92. However, when corrected for altitude difference (see later), the difference is reduced to 9.43%. The stated uncertainties of the absolute UV measurements of the UGA/EPA and USDA instruments are $\pm$5%. Therefore, the data from both sites lie within the measurement errors.

The larger differences between the correlations of the collected data at Big Bend may be due to the local climatology and the separation between the two "colocated" instruments ($\sim$40 km), as well as to an altitude difference (461 m). At the Everglades site, both instruments are located in close proximity to each other, essentially each having the same sky view. In addition, the horizon at the Everglades is not influenced by mountain ranges as the surrounding topography is flat and at sea level. These factors combine to give us the tight regression and minimal scatter between the two data series. The Big Bend instruments are not as closely colocated as the instruments at the Everglades site, since their separation is about 40 km. The Brewer instrument is located on the eastern side of a small mountain range, which receives an annual rainfall of about 14 in./yr, while the USDA instrument is located on the western side of the same range with an annual rainfall of 9.3 in. (personal communication NUVMC site operator). The site of the Brewer instrument experiences more drizzle and ground fog, especially in the winter. From the plot of the data, it seems that there exists a significant variability in the day-to-day measured values of the colocated instruments. The scatter within the plot is much greater than that for the Everglades site, indicating that the sky conditions for the two instruments at Big Bend can be somewhat different on many days for a significant fraction of the day.

It is of interest to examine further the source of the larger scatter in the data at the Big Bend site when compared to the Everglades site that may be due to sky condition variability resulting from the different instrument locations at the Big Bend site. Using the collected Brewer data only and the algorithm previously discussed to determine clear sky days (CSDs), we rejected all data (both USDA and UGA) that was not flagged as a CSD for the majority of the day. Assumptions were made that in such CSD conditions, both instruments had no clouds in their field of view for the course of the day. Figure 2 shows a scatter plot of CSD data for the Everglades and Big Bend data and is reduced in sample size when presented for CSDs only. The climatology of the Everglades region (subtropical wetlands) means that the number of days with clear skies is limited. However, the drier inland desertlike region of the Big Bend National Park has a greater number of CSDs. For the Everglades CSD data the broadband USDA instrument data is 1.6% lower than the recorded data from the UGA/EPA instrument with an R^2 value of 0.99. At the Big Bend site, for CSDs, the USDA data is 9.3% (6.3% when corrected for altitude) lower than that of UGA/EPA, with a lower R^2 value of 0.985. These average differences are similar to those of the all sky conditions data and are still within the estimated measurement errors of the respective instruments. The Big Bend data for CSD has a much higher R^2 value of 0.985 for CSD compared to the 0.92 for the all sky conditions, indicating a better correlation of the data in these conditions, supporting the idea that differences in sky conditions at the sites of the two instruments are the main source of the scatter.

The daily DUV ratios of the USDA data to the UGA/EPA data, plotted as a function of the SZA at 1 pm local time, are shown in Fig. 3. The daily DUV for the Big Bend site shows a larger deviation between the USDA and UGA/EPA for days with larger SZAs at solar noon (lower sun elevation near winter solstice), when compared to data taken on days with smaller minimum SZAs (higher sun elevation near summer solstice). A similar trend is noted for the Everglades data. This is confirmed from data shown in Table 3 by comparing averages of the ratios of the daily erythemally weighted irradiance of the two instruments at a given site for days with smaller and larger solar noon SZAs. For Big Bend, the average ratio of 0.931 for days with solar noon SZAs between 5 and 20 deg, drops to 0.918 for SZAs between 35 and 50 deg. A drop in the ratio from 0.981 to 0.946 occurs at the Everglades site for these same minimum daily SZAs. A dependence of the ratio of the irradiance measured by the two instruments on minimum daily SZA during the day suggests that the two instruments may have a different angular response for their collectors. A difference in the irradiance values resulting from cosine response errors should become more pronounced with a decrease in the elevation of the sun above the horizon as indicated by the data. Since the UGA/EPA Brewers at both sites are characterized for their angular responses, whereas the USDA broadband instruments are not individually calibrated, the increased difference at larger solar noon SZAs may indicate an error in the angular response of the USDA instruments; however, further analysis of other data sets is required before this can be verified. In addition, lower SZAs occur in the winter when total ozone is lower at both sites. As explained later in this section, when the total ozone is lower the YES UV-B1 radiometers measure less erythema than the true erythema.

Since long-term trend studies require a high level of stability of the instruments, an evaluation of instrument stability is of utmost importance. The instruments' response will change throughout the annual cycle due to changes in the optical alignment or deterioration of optical components and filters resulting from environmental exposure. In analyzing data from both networks a best attempt is made to account for these changes in response. For example, the UGA/EPA network uses a linear interpolation of the response at two calibrations to define the daily response. The USDA instruments undergo more frequent calibrations (biannual) making their network less susceptible to assumptions about response between calibrations. Data on the ratio of the USDA broadband erythemal UV irradiance values and the daily UGA/EPA Brewer erythemal UV values is shown in Table 3 with the SD indicated in parenthesis. If either instrument were unstable in its response, this ratio would vary with time. As seen in Table 3, the average annual ratio is quite stable for both sites. At Big Bend it falls in the range of 0.894 to 0.946, yielding an average annual response ratio that varies less than 5% over a 6-yr period. For the Everglades site the variation in the ratio is less than 4%.

Changes in relative response of this magnitude are to be expected given the uncertainties in the calibration uncertainties for each instrument and the assumptions used in interpolating between calibrations. The ratio of daily erythemally weighted irradiance values were also grouped according to season. At both sites, the winter and fall seasons showed somewhat lower ratios of USDA/UGA. This probably results from the same cause as the dependence of this ratio on solar noon SZA; i.e., it is related to errors in the cosine response of one or both instruments or the not taking into account total ozone in the erythema calibration factors. Nonetheless, the ratio of USDA/UGA for all seasons, except for fall at Big Bend, is within the estimated errors of the measurements.

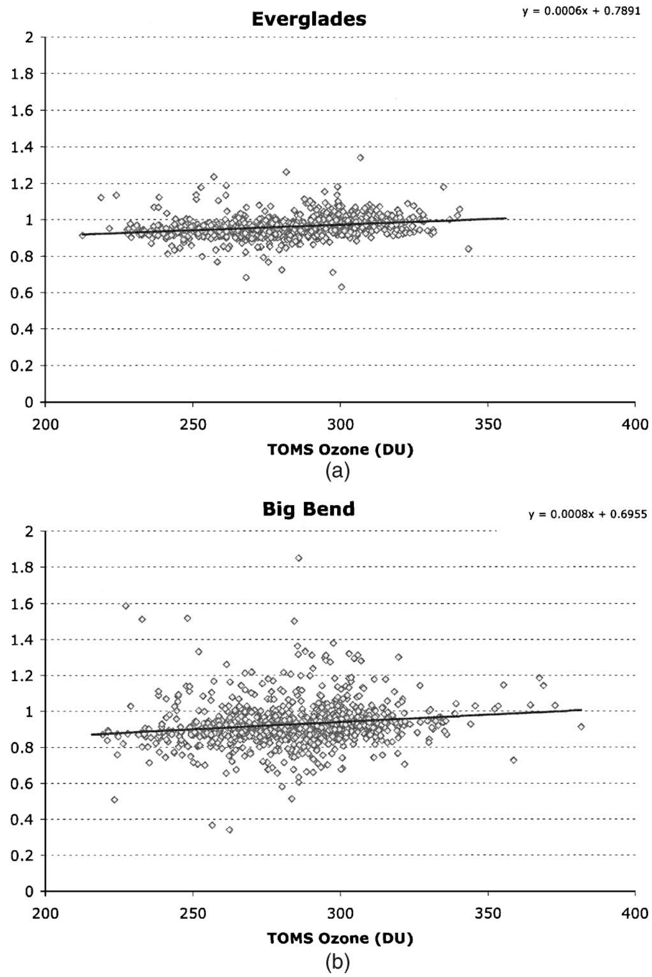

Fig. 4 Daily erythemal UV irradiances versus TOMS total column ozone for (a) Everglades and (b) Big Bend.

The ratio of the USDA/UGA data for the Big Bend site, averaged over all seasons, is lower than that of the Everglades site. In addition, the SDs of the individual seasons are larger at the Big Bend site compared with those of the Everglades site. This is a further indication of the fact that the instruments at Big Bend site are looking at somewhat different sky conditions during the measurement period. One source of the smaller ratio at Big Bend is the altitude difference of the two sites (UGA, 1131 m; USDA, 670 m). Calculations by Barton and Paltridge[12] found that an increase in height of 1 km above sea level resulted in a 15% increase in the erythemal (sunburn) dose. Results by McKenzie[13] predict a 10% increase in the UV irradiance due to a loss of air pressure affecting Rayleigh scattering at a height of 2 km. A conservative 7%/km altitude correction for the Big Bend site would increase the USDA/UGA ratio

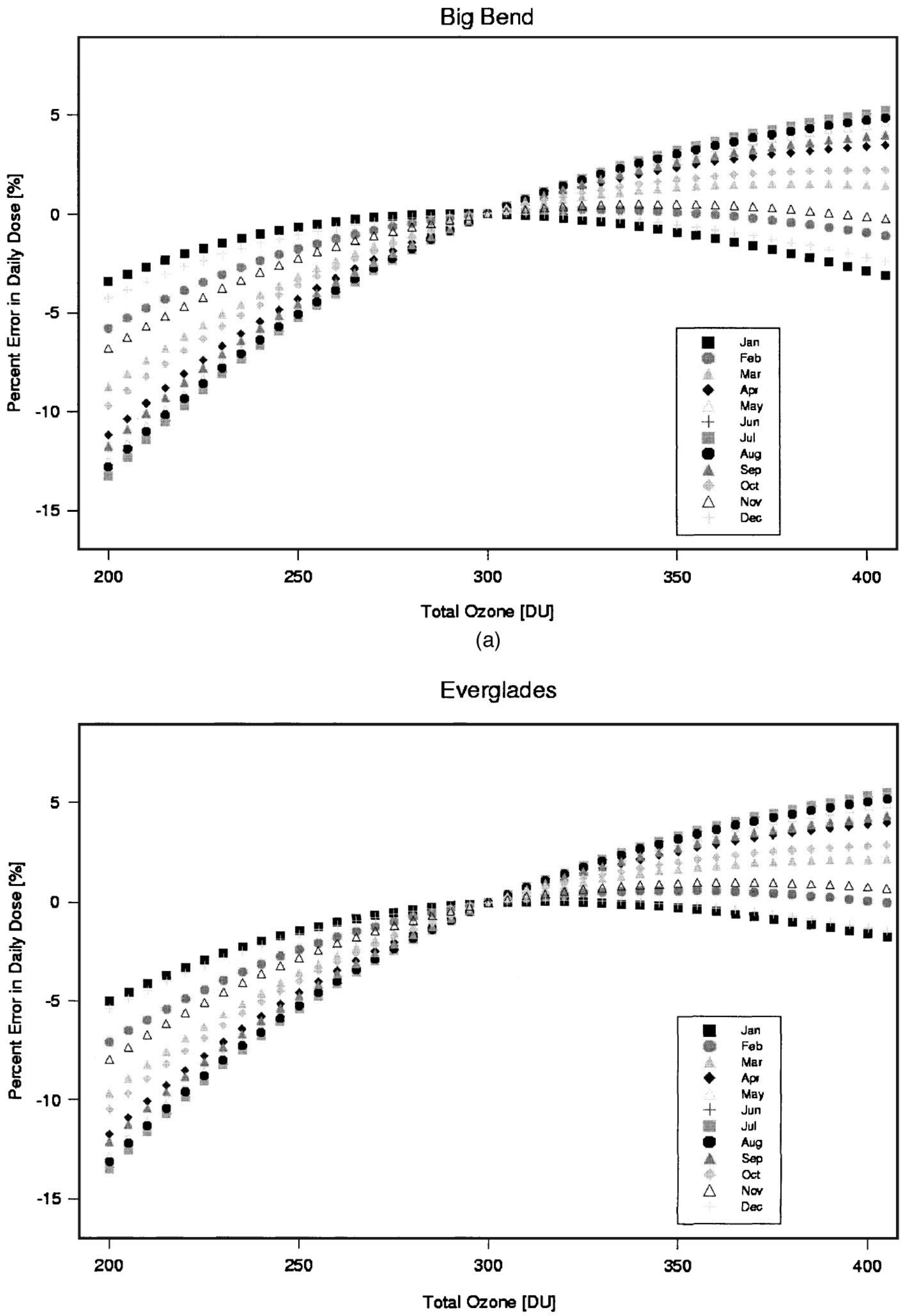

Fig. 5 Percent error on the daily erythema dose as a function of total ozone when assuming a total ozone of 300 DU for (a) Big Bend, Texas, and (b) Everglades, Florida, for 12 months of the year.

by about 3%, bringing the ratio from 0.916 to 0.943, a value that is only 2% below that of the Everglades site. Of course, one should also account for the climatological difference between the sites of the two Big Bend instruments, but one cannot do this quantitatively with the data presented in this paper. Ignoring the climatological differences, a comparison of the two types of instruments at two sites suggests that irradiance measurements by the USDA instruments are about 4% less than those of the UGA/EPA spectroradiometer instruments. Such a difference is within the estimated absolute uncertainties of the two instruments.

As stated earlier, erythema calibration factors were used that assume a total ozone of 300 DU. There is expected to be a difference between the UGA/EPA daily dose and the USDA daily dose as a function of ozone.[7] Several researchers have reported on this ozone dependence.[14] To see the magnitude of the effect, Fig. 4 gives the daily DUV ratios of the USDA data to the UGA/EPA data plotted as a function of TOMS ozone. As expected there is a significant ozone dependence, indicating that the USDA instrument records slightly lower values than the Brewer at lower ozone values. A similar trend is noted for the Everglades data. The Brewer, as it is a scanning spectral instrument, does not show such measurement dependence on ozone. For comparison, Fig. 4 shows the uncertainties in the daily dose for the two sites as a function of total ozone for the ozone range typical of each site for each month of the year for the UV-B1 radiometer. When the total ozone is 300 DU the uncertainty contribution to the daily dose is zero, but can be as much as −13% for low ozone to +5% for high ozone. This is consistent with what is seen in Fig. 5.

4 Conclusions

The data collected in this paper show that the USDA broadband erythemal detector and the UGA/EPA Brewer spectrophotometer produce daily erythemal irradiance data whose ratios are in agreement within the estimated absolute uncertainties of the two instruments. The differences between the collected data were smallest at the Everglades site (3.3%) and largest at the Big Bend site (8.4%). About 3% of the difference at Big Bend can be accounted for by the altitude difference of the location of the two instruments. However, as shown by the significantly larger correlation coefficients for the Big Bend data, even when the colocated instruments are located relatively close to each other (40 km), the instruments can observe a different sky view.

This different sky view results from differences in the obstructions near the horizon and the different cloud and aerosol conditions at these nearby sites. The clear sky day analysis improved the correlations and the scatter of the two data sets, in particular, for the Big Bend site; however, the number of data points used in the analysis decreased. Studies of the USDA/UGA (EPA) daily erythemal UV ratios as a function of SZA and ozone indicate that the USDA erythemal UV irradiance values require small corrections associated with SZA and in the spectral distribution associated with changes in ozone.

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References

1. R. L. McKenzie, W. A. Matthews, and P. V. Johnston, ''The relationship between erythemal UV and ozone, derived from spectral irradiance measurements,'' *Geophys. Res. Lett.* **18**(12), 2269–2272 (1991).
2. S. Madronich, R. L. McKenzie, L. O. Bjorn, and M. M. Caldwell, ''Changes in biologically active ultraviolet radiation reaching the earth's surface,'' *Photochem. Photobiol. B* **46**, 5–19 (1998).
3. J. C. van der Leun and F. R. de Gruijl, ''Climate change and skin cancer,'' *Photochem. Photobiol. Sci.* **1**, 324–326 (2002).
4. Sci-Tec, *Brewer MKIV Spectrophotometer Operator's Manual*, OM-BA-C231 REV B, SCI-TEC Instruments Inc. (1999).
5. R. D. Rundel, ''Computation of spectral distribution and intensity of solar UVB radiation,'' in *Stratospheric Ozone Reduction, Solar Ultraviolet Radiation and Plant Life*, R. C. Worrest and M. M. Caldwell, Eds., Springer-Verlag, Berlin (1986).
6. E. Weatherhead, D. Theisen, A. Stevermer, J. Enagonio, B. Rabinovitch, P. Disterhoft, K. Lantz, R. Meltzer, J. Sabburg, J. DeLuisi, J. Rives, and J. Shreffler, ''Temperature dependence of the Brewer ultraviolet data,'' *J. Geophys. Res.* **106**, 34121–34129 (2001).
7. K. O. Lantz, P. Disterhoft, J. J. DeLuisi, E. Early, A. Thompson, D. Bigelow, and J. Slusser, ''Methodology for deriving clear-sky erythemal calibration factors for UV broadband radiometers of the Central UV Calibration Facility,'' *J. Atmos. Ocean. Technol.* **16**, 1736–1752 (1999).
8. I. J. Barton and G. W. Paltridge, ''The Australian climatology of biologically-effective ultraviolet radiation,'' *Australas J. Dermatol.* **20**, 68–74 (1979).
9. R. L. McKenzie, B. Conner, and G. Bodeker, ''Increased summertime UV radiation in New Zealand in response to ozone loss,'' *Science* **285**, 1709–1711 (1999).
10. D. S. Berger, ''The sunburning ultraviolet meter: design and performance,'' *Photochem. Photobiol.* **24**, 587–593 (1976).
11. G. Bernhard and G. Seckmeyer, ''Uncertainty of spectral solar UV irradiance,'' *J. Geophys. Res.* **104**, 14321–14345 (1999).
12. K. Leszczynski, K. Jokela, L. Ylianttila, R. Visuri, and M. Blumthaler, ''Report of the WMO/STUK intercomparison of erythemally weighted solar UV radiometers,'' WMO/GAW Report No. 112 (1995).
13. B. Mayer and G. Seckmeyer, ''All-weather comparison between spectral and broadband (Robertson-Berger) UV measurements,'' *Photochem. Photobiol.* **64**(5), 792–799 (1996).
14. M. Nunez, C. Kuchinke, and P. Gies, ''Using broadband erythemal UV instruments to measure relative irradiance,'' *J. Geophys. Res.* **107**(D24), 4789 (2002).

Biographies and photographs of the authors not available.