Methodology for Deriving Clear-Sky Erythemal Calibration Factors for UV Broadband Radiometers of the U.S. Central UV Calibration Facility

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ABSTRACT

In the United States, there are several federal agencies interested in the effects of UV radiation, which has resulted in the establishment of UV monitoring programs each with their own instrumentation and sites designed to address their specific needs. In 1993, participating agencies of the U.S. Global Change Research Program organized a UV Panel for coordinating the different agencies' programs in order to ensure that UV data are intercalibrated, have common quality assurance and control procedures, and that the efforts among agencies are not duplicated.

In order to achieve these goals, in 1994 the UV Panel recommended formation of the U.S. Central UV Calibration Facility (CUCF), which is operated by the Surface Radiation and Research Branch of the Air Resources Laboratory of National and Oceanic Atmospheric Administration. The CUCF is responsible for characterizing and calibrating UV measuring instruments from several U.S. federal agencies. Part of this effort is to calibrate UVB broadband radiometers from these agencies. The CUCF has three Yankee Environmental Systems (YES UVB-1) and three Solar Light (SL 501A) broadband radiometers as reference standards that are routinely calibrated. For the past three years, clear-sky erythema calibration factors were determined for these standard UVB broadband radiometers by using simultaneously measured erythema-weighted irradiance determined during the annual North American Intercomparison. Comparisons between erythemally weighted irradiance calculated spectra supplied by spectroradiometers typically agreed better than $\pm 2\%$ for solar zenith angles less than 60°. The spectroradiometers were participating in an intercomparison event organized by the National Institute of Standards and Technology and the CUCF.

In this article, the calibration methodology is described for transferring the calibration from the spectroradiometers to the CUCF's standard broadband radiometers. The CUCF standard broadband radiometers are used to calibrate UVB broadband radiometers from several U.S. UV monitoring networks. Erythemal calibration factors for the CUCF's YES UVB-1 standard broadband radiometer triad are reported for 1994, 1995, and 1996. Erythemal calibration factors for CUCF's SL 501A standard broadband radiometer triad are reported for 1996.

1. Introduction

Decreases in the concentration of stratospheric ozone in Antarctica and around the globe have led to concerns about increasing levels of ultraviolet radiation (UV) reaching the troposphere (Lubin and Frederick 1990; Stolarski et al. 1992; Kerr et al. 1993; Reinsel et al. 1994; Madronich 1992, 1995; Kelfkens et al. 1990). The concern arises because of the potentially detrimental impact of increased UV radiation on human health, the biosphere, air quality, and degradation of materials (Tevini 1993; UNEP 1994). However, ozone represents only one parameter that determines the variability and trends in UV radiation at the earth's surface. Other factors

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include cloud cover, aerosol, and UV-absorbing gases. Uncertainties in the climatology and changes in UV radiation reaching the surface of the earth and subsequent effects on human health and the environment have led to the establishment of surface-based UV monitoring programs worldwide.

In the United States there are several federal agencies concerned with the effects of UV radiation, which has resulted in the establishment of several UV monitoring programs each with their own instrumentation and sites designed to address their specific needs. In 1993, participating agencies of the U.S. Global Change Research Program's (USGCRP) organized a UV Panel for coordinating the different agencies programs in order to ensure a common calibration link for data comparability, common quality assurance and control procedures, and nonredundancy of efforts (USGCRP 1995). The UV Panel recommended that one central calibration facility for the U.S. UV monitoring networks was essential in order to achieve internetwork data comparability in a cost-effective manner. This decision resulted in the formation of the Central UV Calibration Facility (CUCF) in 1995, which is operated by the Surface Radiation and Research Branch (SRRB) of the Air Resources Laboratory (ARL) of the National Oceanic and Atmospheric Administration (NOAA).

At present there are different types of UV monitoring instruments, including spectroradiometers, narrowband filter radiometers, and broadband radiometers. The UV broadband radiometer is the most ubiquitous of UV measuring instruments because of radiometer's relatively low cost, low maintenance requirements, and stability (DeLuisi et al. 1983, 1992). Worldwide agencies and organizations utilize UVB broadband meters and have reported on the broadband's performance, stability, and calibration procedures (Johnsen et al. 1991; DeLuisi et al. 1983, 1992; Grainger et al. 1993; Weatherhead et al. 1997, 1998; Leszczynski et al. 1998). Presently, most of the U.S. UV monitoring networks are using calibration factors supplied by each individual manufacturer. The necessity for a central calibration facility is highlighted by the recent work of Long (1997), who showed significant disparities between UV index data determined from Solar Light, Inc. (SL), and Yankee Environmental Systems (YES) UV broadband radiometers from several U.S. networks. These discrepancies could be due in part to differences in the calibration procedures. The utilization of the calibration factors developed at the CUCF is expected to narrow these discrepancies. In this work, we detail our methodology for calculating clear-sky erythemal calibration factors and their uncertainties for CUCF's standard UV broadband radiometers, that is, YES and SL. These standard broadband radiometers are used as the reference instruments to determine erythemal calibration factors for UV broadband radiometers of the U.S. UV monitoring networks and facilities. In order to globally compare UV measurements between different instrument types, the calibration factors for the UV broadband radiometers are determined using the standardized erythema action spectrum (McKinlay and Diffey 1987), which will be referred to as the erythemal calibration factors (ECF). Conversion from voltage to erythemally weighted irradiance (W m^{-2}) is desirable as a means for comparing measurements from many different UV broadband instrument types. The CUCF also determines calibration factors for each instrument using the instrument's spectral response function, which will provide a means for establishing the stability of a given UV broadband radiometer; however, this is not the purpose of this paper. A comparison of clear-sky erythemally weighted integrated irradiance on clear-sky days from spectroradiometers that were calibrated by the National Institute of Standards and Technology (NIST) and NOAA scientists during the 1994, 1995, and 1996 North American Spectroradiometer Intercomparisons is reported. The ECFs as a function of solar zenith angle and total ozone are determined for the standard triads (YES UVB-1 and SL 501A) and a polynomial fit to the data is given. Also reported is a comparison of erythemal calibration factors of the CUCF's YES UVB-1 broadband radiometers for 1994 and 1995 for the same total ozone concentration.

2. Central ultraviolet calibration facility

The CUCF was formed in 1994 and is operated by the SRRB of the ARL of NOAA. The CUCF consists of three parts: the calibration laboratory, which is located in Boulder Colorado; the Table Mountain Test Facility (TMTF), which is located 15 minutes north of Boulder (40°7′N, 105°14′W) at an elevation of 1.69 km; and the High Altitude Observatory, which is located above the boundary layer (2.9 km) at Niwot Ridge, Colorado (40°2′N, 105°32′W).

In terms of the UVB broadband radiometers, the CUCF is responsible for calibrating the radiometers that are part of NOAA's Integrated Surface Irradiance Study (ISIS) (Hicks et al. 1996; Augustine et al. 1997) and USDA's Ultraviolet Radiation Program (Gibson 1991, 1992; Bigelow et al. 1998). The ISIS network consists of two levels. There are 10 level-1 sites that measure incoming radiation only, and there are 5 level-2 sites with one more site proposed that compose Surface Radiation Budget Network (SURFRAD), which measure the surface radiation budget. Both ISIS levels 1 and 2 measure UVB radiation with level-1 sites using Solar Light (SL 501A) broadband radiometers, and the level-2 sites using Yankee Environmental Systems (YES UVB-1) broadband radiometers. The USDA network currently consists of 27 sites, all of which have at least one YES UVB-1 instrument with several more sites planned. The 15 ISIS UV broadband radiometers are cycled through the CUCF once per year, where they are calibrated by running simultaneously against CUCF's "standard" UVB radiometers in the field at the TMTF. The 27+ YES UV-1 broadband radiometers of the

USDA network started cycling through the CUCF in 1997. In addition to calculating calibration factors, the UVB broadband radiometers of the national UV monitoring networks are tested annually for spectral, absolute, and angular response at the calibration laboratory.

3. General procedure for determining calibration factors

The general ''classic'' procedure for calibrating the UVB broadband radiometers is to compare measurements of the voltage output of the broadband radiometer to concurrent integrated spectral irradiance data weighted with the appropriate spectral response function. The calibration factor $C_f(\theta_0)$ is given by

$$C_f(\theta_0)S(\theta_0) = \int_\lambda E(\lambda,\ \theta_0)R(\lambda)\ d\lambda, \qquad (1)$$

where $S(\theta_0)$ is the broadband radiometer signal in volts; $E(\lambda,\ \theta_0)$ is the spectroradiometer irradiance data in watts per square meter that has been corrected for scanning times, wavelength range, and angular response as discussed in the next section; and $R(\lambda)$ is the desired action spectrum or spectral response function. An instrumental calibration of the UVB broadband radiometer is performed using Eq. (1) above, where $R(\lambda)$ is the instrument's measured spectral response function. Because the spectral response functions are not exactly the same among UVB broadband instruments even of the same manufacturer, the Cf's that are determined in this fashion could not be used to compare output between different instrument types (e.g., Solar Light, YES UVB-1). Therefore, to compare the readings of different instrument types a common spectral response function is chosen for $R(\lambda)$. The spectral response function chosen is the CIE-accepted erythema action spectrum of McKinlay and Diffey (1987). The ECF for the UVB broadbands are used for converting the voltage output of the broadband radiometers (V) to an erythemally weighted irradiance (W m^{-2}). The ECFs will correct for voltage drifts that may exist in the UV broadband radiometers due to changes in sensitivity, spectral response, and angular response. Because the spectral response of the UVB radiometers does not perfectly simulate the McKinlay–Diffey action spectrum, the erythemal calibration factors are dependent on all variables that affect the wavelength distribution of solar irradiance in the erythemal wavelength band. The most significant parameters are the solar zenith angle and total ozone, which are discussed below. The calibration factor determined by Eq. (1) inherently corrects for the angular error of the broadband radiometer under the observed atmospheric conditions. Specifically, the right side of Eq. (1) is considered the ''true'' spectrally weighted irradiance, and $Cf(\theta)$ is the factor that the instrument's voltage must be multiplied by to give the true weighted irradiance. This is done as a function of zenith angle, and therefore the $Cf(\theta)$ includes the angular correction to the instrument's output to get the actual weighted irradiance under the given atmospheric conditions. However, the ECFs are calculated for clear-sky conditions and are essentially clear-sky erythemal calibration factors. Under different atmospheric conditions, the ECFs as a function of zenith angle will be different. This is because the radiometer's angular response error will cause different outputs, depending on the spatial distribution of the radiation field.

The erythemal calibration factors of the six standard radiometers that reside at the Table Mountain Test Facility are calculated annually by CUCF by comparing against UV irradiance from spectroradiometer(s) weighted with the CIE erythema action spectrum. In 1994, 1995, and 1996 the standard radiometers were compared against spectroradiometers that participated in the North American Spectroradiometer Intercomparison. The erythema calibration factors of CUCF's standards reported in this work are for 1994, 1995, and 1996 and will only be used for calibrating the ISIS and SURFRAD network UVB radiometers. A USDA U1000 reference spectroradiometer will permanently reside at the TMTF and will be used for future calibrations of the triad with a Brewer MKIV spectroradiometer used as a check. A calibration history of the standards against the U1000 spectroradiometer will be determined through out the year using the procedure described here. In the next sections, a description of the instrumentation, the procedure for ensuring that the spectroradiometer spectral data are accurate, and data quality control procedures are given.

4. Instrumentation

a. Broadband radiometers

The standard UV radiometers are located at Table Mountain Test Facility and include three YES UVB-1 radiometers, acquired in 1994 with serial numbers 940401, 940402, and 940404 and three SL 501A radiometers, acquired in 1996 with serial numbers 1916, 2004, and 2005. The UV broadband radiometers are designed to approximate the sun-reddening (erythema) response in human skin to solar radiation. The precursor to these instruments is the Robertson–Berger meter where the basic design has remained relatively the same except for several minor modifications including temperature control (Robertson 1972; Berger 1976; Dichter 1993). In these instruments, solar radiation strikes the top of the dome where only ultraviolet radiation and a small amount of red light are transmitted by a UG-11 Schott filter. A phosphor layer that is deposited on an underlying Corning 4010 postfilter absorbs UV radiation and emits in the green part of the spectrum. Green light is transmitted through the postfilter and detected by a photosensor. The Solar Light instrument is maintained at 25°C and the YES instrument is thermostatically controlled at 45°C with an internal thermistor and feedback control system.

b. Spectroradiometers

The spectroradiometric data used in this study is from spectroradiometers corresponding to several different UV monitoring networks that participated in the 1994, 1995, and 1996 North American UV Spectroradiometer Intercomparisons. In 1994, there were four spectroradiometers: two Brewer Spectrophotometers, Model MKII, serial numbers 009 and 113 from the Atmospheric Environment Service of Canada (AES1 and AES2, respectively) from Canada's UV monitoring network; a third Brewer Spectrophotometer, Model MKIV, serial number 109, operated by the University of Georgia, which manages the Environmental Protection Agency's (EPA) UV monitoring network; and a Biospherical Instruments SUV-100 Ultraviolet Spectroradiometer, serial number B-007, which is operated by Biospherical Inc. for the National Science Foundation's (NSF) Polar Programs UV monitoring network. In 1995, three spectroradiometers participated in the intercomparison: one Brewer Spectrophotometer, Model MKII, serial number 039, operated by AES Canada; a second Brewer Spectrophotometer, Model MKIV, serial number 114, from the EPA network; and a Biospherical Instruments SUV-100, which is the same instrument as the year before operated by the Biospherical Instruments for the NSF network. In 1996, there were two spectroradiometers in use: the AES operated one of their new double monochromators which was a Brewer Spectrophotometer, Model MKIII, serial number 085; and a second Brewer Spectrophotometer, Model MKVI, serial number 101, administered by the University of Georgia. The EPA spectrophotometer, serial number 101, from the 1996 intercomparison is currently located at CUCF's Table Mountain Test Facility. The lamps used to determine the responsivities of the spectroradiometers were NIST working standard 1000-W modified FEL-type designated OS-27 for 1994, F-332 for 1995, and E004 for 1996. These working standard lamps were calibrated in the horizontal position by NIST.

5. Calibration and data quality control of the spectroradiometers

a. Spectroradiometer calibration

The calibration of the spectroradiometers is described in annual reports of the North American Intercomparisons (Thompson et al. 1997; Early et al. 1998) and readers are encouraged to refer to these reports for important details of the instrumentation, explicit calibration procedures, and results. We present a general overview of the results pertaining to the calibration of the UV broadband radiometers. The instruments that participated in the intercomparisons are characterized for stray-light rejection and slit-scattering function, bandwidth, wavelength accuracy, and spectral responsivity. Stray-light rejection and the slit-scattering function are determined with the 325.029-nm line of a HeCd laser. Wavelength calibration and wavelength registration were performed with a Hg lamp internal to each instrument. Wavelength accuracy was checked with an external Hg lamp and the HeCd laser; in 1995 and 1996 several singlet lines from an external Cd lamp were used for an additional wavelength accuracy check, and in 1996 lines from a Zn lamp were also included in the wavelength accuracy analysis. Most importantly, spectral irradiance responsivity of each instrument was accomplished using an NIST working standard 1000-W FEL quartz halogen lamp. In the three intercomparisons, the Brewer (AES and EPA) instruments had a nominal bandwidth of 0.6 nm and the NSF instrument had a bandwidth of 0.95 nm. The bandwidths of all the instruments decreased with increasing wavelength as determined from the Hg, Cd, and Zn singlet lines and the HeCd line ranging between −0.2% and −0.4% per nanometer. In 1994 and 1995, the stray-light rejection was at least 10^{-4} for the Brewer instruments (AES and EPA), and 10^{-5} for the NSF instrument. In 1996, the AES operated a double monochromator that had a stray-light rejection of 10^{-8}. A stray-light rejection of 10^{-4} is marginally acceptable for determining the erythematogenic irradiance at high sun. The overall wavelength accuracy of the spectroradiometers was less than approximately ±0.08 nm for the AES and EPA instrument, and less than ±0.2 nm for the NSF instrument.

b. Data preparation and quality control

During each of the intercomparisons, the various UV monitoring instruments were run synchronously for approximately one week. The solar ultraviolet irradiance $E(\lambda)$ was calculated from the measured signals $S(\lambda)$ and the responsivity $R_s(\lambda)$, as determined by the NIST standard lamp(s) for each instrument;

$$E(\lambda) = S(\lambda)/R_s(\lambda). \tag{2}$$

The spectroradiometric solar irradiance scans were run synchronously starting every half hour beginning at 290 nm with a 0.25-nm step size. The annual report of the North American Spectroradiometer Intercomparison (Thompson et al. 1997) describes a thorough comparison of the spectroradiometric data from the synchronous spectral scans, which includes an analysis of the spatial and temporal stability; however, in this paper we are specifically concerned with the comparison of the erythemally weighted integrated spectral data during a clear-sky day from the different spectroradiometers. Therefore, the following is a comparison of the erythemally weighted integrated spectral data for each of the spectroradiometers for 1994, 1995, and 1996. The erythemally weighted irradiance is determined by con-

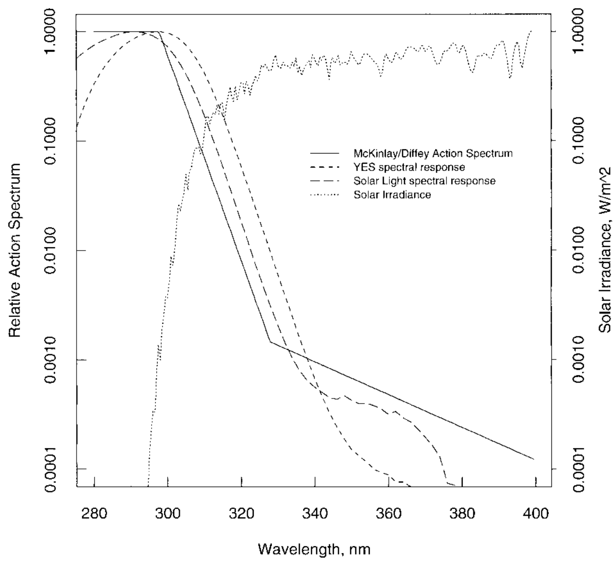

FIG. 1. McKinlay–Diffey action spectrum, Yankee Environmental Systems (YES) spectral response function, Solar Light spectral response function, and spectral solar irradiance measurements (W m^{-2}) at zenith angle = 40°.

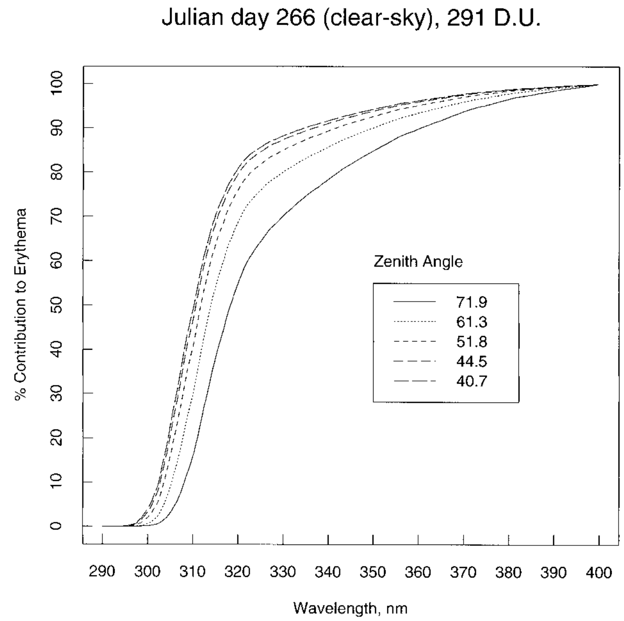

FIG. 2. Relative contribution of the erythemally weighted irradiance as the wavelength is increased from 280 to 400 nm.

voluting the erythema action spectrum given in Fig. 1 from 290 to 400 nm with the measured irradiance. However, the spectral irradiance measured by the AES instruments extends only from 290 to 325 nm and the EPA and NSF instrument extends from 290 to 363 nm. Even though the erythema action spectrum drops significantly toward longer wavelengths, the solar spectrum is rising sharply and the contribution from 325 to 400 nm can be significant. Figure 2 shows the contribution of each additional wavelength to the total integrated erythemal value from 280–400 nm on Julian day 266, which is a clear-sky day with a total ozone concentration of 293 D.U. Note the very sharp cutoff below 300 nm. This is caused by the increasingly powerful UV absorption by ozone as the wavelength decreases. At a zenith angle of 40.7°, the contribution from 325 to 400 nm is about 10% of the total erythemal value (290–400 nm), and at a zenith angle of 71.9° the contribution is approximately 30%. Because the spectroradiometer could not measure out to 400 nm, the irradiance was modeled for each day with a discrete ordinates radiative transfer model (Stamnes et al. 1988; S. Madronich 1997, personal communication) using concurrently observed total ozone. The modeled spectral irradiance values were normalized to the measurements by overlapping the last 10 nm.

In this study, only clear-sky data were used in the determination of the erythemal calibration factors. During the week of each of the intercomparisons, there were two clear-sky days in 1994, 23–24 September, which are Julian days 266 and 267; two clear days in 1995, 18 July (1200–2100 GMT) and 19 June (1200–2000 GMT), which are Julian days 169 and 170; and two clear-sky days in 1996 on 18 and 23 June (1200–2130 GMT), which are Julian days 171 and 175. Clear-sky days were verified by observing pyranometer, UV broadband data, and aerosol optical depth observations. During the 1994 intercomparison, the spectroradiometer measurements were started every half hour with a scanning speed of 3 s nm^{-1}. Because the spectroradiometers are scanning instruments, the measurements needed to be corrected for scanning time in order to compare to the broadband measurements that inherently measure all wavelengths simultaneously. In this study, the 1-min average of 1-s broadband measurements made at every half hour was compared to the spectroradiometer measurements that start scanning on the half hour. If the spectroradiometer data were not corrected for scanning time, the measurements in the afternoon would overweight the longer wavelengths as compared to the broadband data and would underestimate the longer wavelengths in the morning scans. If these measurements were not corrected for these particular scanning times, the erythemally weighted spectroradiometer irradiance measurements would be 3% too high at 2 h after local noon and 3% too low at 2 h before local noon. The spectral data are corrected for scanning time by plotting each wavelength as a function of measurement and fitting the data with a cubic spline and interpolating to the value at every half hour.

c. Angular corrections to spectroradiometer measurements

The irradiance on a flat plate surface varies as the cosine of the angle of incidence, θ, where θ is the angle between the incident beam and the normal to the surface.

In practice, irradiance collectors tend to deviate from this ideal cosine response because of imperfect irradiance collection optics (DeLuisi and Harris 1981, 1983). Information that is needed to correct irradiance measurements for the nonideal angular response of the instrument include the cosine response of the instrument in a finite number of planes perpendicular to the diffuser plate, the proportion of diffuse and direct irradiance, and the sky radiance distribution. However, information on these details of the instrument and the sky radiance are not available. The following gives a description of the procedure used to correct the spectroradiometers for their angular error.

The relative angular response, $A(\theta)$, for the Brewer spectroradiometer was measured for zenith angles of 0°–85° (J. Rives and W. Mou 1996, personal communication). These measurements were repeated at intervals of 90° in azimuth and the responses were approximately azimuthally independent. The average of the four azimuths was used in the following analysis and had a standard error of less than 3% for all zenith angles. The relative angular error is given by the relative angular response divided by the ideal cosine response, $A'(\theta) = A(\theta)\cos\theta$. The relative angular error is applied to the direct irradiance and the sky radiance. The direct irradiance and the sky radiance distribution were estimated using a 16-stream discrete ordinates radiative transfer model [K. Stamnes et al. 1988; S. Madronich 1997, personal communication) using typical total ozone measurements and total aerosol optical depth measurements for the site. The correction factor, C, for the spectroradiometer measurements at a given solar zenith angle (θ_0) is determined by the following:

$$C(\theta_0) = E_{\rm act}(\theta_0)/E_{\rm err}(\theta_0). \quad (3)$$

The actual or true irradiance $E_{\rm act}(\theta_0)$ at solar zenith angle θ_0 is given by

$$E_{\rm act}(\theta_0) = \int_\phi \int_\theta \int_\lambda L(\theta, \phi, \lambda) \cos\theta \sin\theta \, d\theta \, d\phi \, d\lambda, \quad (4)$$

where L is the radiance. For clear skies, the radiation field can be divided into direct and diffuse components and the radiation field is assumed to be azimuthally independent. The total irradiance is then given by

$$E_{\rm act}(\theta_0) = 2\pi\left[\cos\theta_0 \int_\lambda E_{\rm dir}(\lambda, \theta_0)\, d\lambda + \int_\theta \int_\lambda L_{\rm diff}(\theta, \lambda) \cos\theta \sin\theta \, d\theta \, d\lambda\right]. \quad (5)$$

The measured irradiance including the spectroradiometer's angular error is given by

TABLE 1. Angular correction factors (ACFs) for the spectroradiometer measurements for 1994.

SZA*	ACF	SZA	ACF
15	1.026	54	1.058
20	1.028	56	1.061
25	1.031	58	1.063
30	1.035	60	1.066
35	1.038	62	1.069
40	1.041	64	1.072
42	1.043	66	1.074
44	1.045	68	1.076
46	1.047	70	1.078
48	1.049	72	1.080
50	1.052	74	1.081
52	1.055	75	1.081

* SZA is the solar zenith angle.

$$E_{\rm err}(\theta_0) = 2\pi\left[A'(\theta_0)\cos\theta_0 \int_\lambda E_{\rm dir}(\lambda, \theta_0)\, d\lambda + \int_\theta \int_\lambda A'(\theta) L_{\rm diff}(\theta, \lambda) \cos\theta \sin\theta \, d\theta \, d\lambda\right], \quad (6)$$

where $A'(\theta)$ is the irradiance collector's averaged relative angular error as defined above.

The correction factors, C, for the spectroradiometric irradiance measurements as a function of solar zenith angle are given in Table 1. The finalized calibration factors in Figs. 10a,b and Tables 4 and 5 were multiplied by the values given in Table 1 at the appropriate solar zenith angle. There are several uncertainties associated with the angular correction to the spectroradiometer measurements. These include random and systematic uncertainties that arise from the measurement of the angular response of the spectroradiometer, uncertainties in model inputs for the calculation of the sky radiance distribution, and uncertainties in the calculation of the contribution of the diffuse and direct irradiance to the total irradiance (Seckmeyer and Bernhard 1993; Grobner 1996). Propagation of the random uncertainties from the azimuthal average of the angular measurements causes approximately a ±2% error in the corrections to the data. The uncertainty in the angular correction due to the uncertainties in inputs for the calculation of the sky radiance distribution is approximately ±2%. The combined uncertainty of the cosine correction is ±2.8%. Nevertheless, the corrections bring the observed values closer to the true values.

d. Data analysis of integrated erythemally weighted spectroradiometer measurements

Table 2 gives the year, day, time, lamp number, and instrument temperature for the lamp scans used for the determination of the responsivities of the spectroradiometers. The year, day, time, instrument, and temper-

TABLE 2. Year, day, time, spectroradiometer, lamp, and temperature of lamp irradiance scans used to determine the responsivity for the determination of the solar irradiance.

Year	Day	Time (h)	Instrument	NIST Lamp	Temperature (°C)
1994	264	1500	AES-1	OS-27	29.6
	263	2330	AES-2	OS-27	33.3
	262	2230	EPA	OS-27	32.3
	262	1515	NSF	OS-27	32.5
1995	172	2148	AES	F-332	40.6
	170	0001	EPA	F-332	35.9
	172	2328	EPA	F-332	36.4
	170	0115	NSF	F-332	—
	173	1607	NSF	F-332	—
1996	171	2330	AES	E-004	43.2
	174	0012	AES	E-004	32.0
	174	1818	AES	E-004	30.3
	172	0048	EPA	E-004	32.5
	173	2212	EPA	E-004	29.9
	174	2200	EPA	E-004	26.4

ature of the synchronized clear-sky spectroradiometer scans that are used for determining the true erythemally weighted irradiance are given in Table 3. Since the erythemal calibration factors are dependent on the total ozone, total ozone from the EPA and AES Brewer measurements are given in Fig. 3. The clear-sky erythemally weighted irradiance data for the four spectroradiometers of the first intercomparison excluding cosine corrections are given in Figs. 4a,b. Figure 5 shows the ratio of the clear-sky erythemally weighted irradiance of each of the instruments to the average of the erythemally weighted irradiance from all the instruments; however, the average excludes instruments that were problematic on a given day (e.g., AES-1 on day 266, AES on days 169 and 170.) One obvious feature is that AES-1 is significantly lower than the other instruments on Julian day 266. On this particular day, the AES-1 instrument had a wavelength calibration error; therefore, data were not included in the analysis (Thompson et al. 1997). In 1994, at solar noon the erythema-weighted irradiance for a given instrument is within 1.1% from the average of the erythema-weighted irradiance of all the instruments excluding the stated problematic instruments. However, there is an unexplained drift in the NSF instrument toward larger integrated erythemal values as the day progresses and reaches a 4.4% deviation from the average of the instruments by a zenith angle of 70°. This could be an angular response problem in this particular instrument because the behavior exists in both days as the solar zenith angle increases.

During the 1995 intercomparison, the erythemally weighted integrated irradiance data for the AES instrument on days 169 and 170 were significantly larger than the other instruments, which was due to a short-lived power supply problem (Figs. 5b,c). After it was corrected, this instrument agreed well with the other instruments for the duration of the intercomparison. At

TABLE 3. Year, days, times, spectroradiometer, and temperature of synchronized spectral clear-sky solar ultraviolet irradiance measurements used for determining the broadband erythemal calibration factors. A dash indicates the instruments data was not used, an X indicates the data was used and in parenthesis is the instrument filter temperature (°C).

Year	Day	Time (h)	AES1	AES2	EPA	NSF
1994	266	16.5	—	X(23.6)	—	X
		17.0	—	X(25.8)	X(25.8)	X
		17.5	—	X(27.7)	X(28.4)	X
		18.0	—	X(29.5)	X(29.9)	X
		18.5	—	X(31.0)	X(31.4)	X
		19.0	—	X(31.4)	X(31.8)	X
		19.5	—	X(31.8)	X(31.8)	X
		20.0	—	X(32.0)	X(32.0)	X
		20.5	—	X(32.3)	X(32.3)	X
		21.0	—	X(−)	X(32.7)	X
		21.5	—	X(32.7)	X(32.7)	X
		22.0	—	X(31.3)	X(32.3)	X
		22.5	—	X(32.0)	X(31.9)	X
		23.0	—	X(31.4)	X(31.8)	X
	267	16.0	X(15.6)	X(19.7)	X(20.8)	X
		16.5	—	—	X(22.8)	X
		17.0	X(21.9)	X(25.1)	X(25.4)	X
		17.5	X(23.2)	X(27.8)	X(27.3)	X
		18.0	X(26.9)	X(29.5)	X(29.2)	X
		18.5	X(28.4)	X(31.0)	X(30.7)	X
		19.0	X(28.4)	X(31.9)	X(31.8)	X
		19.5	X(29.9)	X(32.7)	X(32.3)	X
		20.0	X(31.4)	X(33.5)	X(32.7)	X
		20.5	X(31.0)	X(33.8)	X(33.1)	X
		21.0	X(31.9)	X(34.2)	X(33.8)	X
		21.5	X(32.7)	X(34.6)	X(34.2)	X
		22.0	X(32.3)	—	X(34.2)	X
		22.5	X(32.7)	—	X(33.8)	X
		23.0	X(31.8)	—	X(33.4)	X
1995	169	13.5		—	X(14.8)	X
		14.0		—	X(16.7)	X
		14.5		—	X(18.6)	X
		15.0		—	X(20.8)	X
		15.5		—	X(22.8)	X
		16.0		—	X(24.7)	X
		16.5		—	X(26.2)	X
		17.0		—	X(28.1)	X
		17.5		—	X(29.5)	X
		18.0		—	X(30.6)	X
		18.5		—	X(31.8)	X
		19.0		—	X(32.3)	X
		19.5		—	X(33.1)	X
		20.0		—	X(33.1)	X
	170	13.5		—	X(18.2)	X
		14.0		—	X(20.8)	X
		14.5		—	X(22.8)	X
		15.0		—	X(24.7)	X
		15.5		—	X(26.6)	X
		16.0		—	X(28.8)	X
		16.5		—	X(30.3)	X
		17.0		—	X(32.0)	X
		17.5		—	X(33.1)	X
		18.0		—	X(34.2)	X
		18.5		—	X(35.2)	X
		19.0		—	X(36.4)	X
		19.5		—	X(37.2)	X
		20.0		—	X(37.6)	X

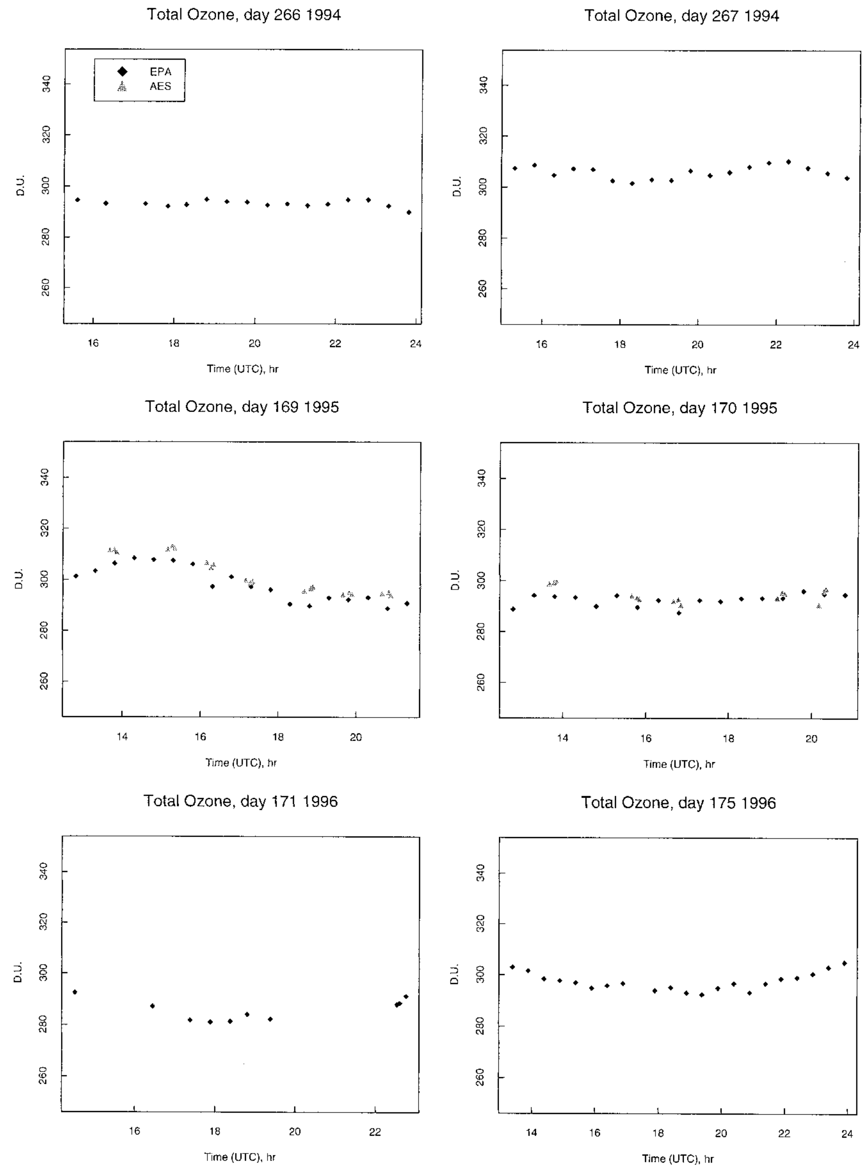

FIG. 3. Total ozone measurements as determined by the EPA and AES Brewer spectrophotometer on clear-sky days during the 1994, 1995, and 1996 intercomparisons.

solar noon, the erythema-weighted irradiance for the NSF was 1.2% higher than the EPA (Figs. 4b,c).

The 1996 intercomparison had only one clear-sky day (175) and several instrument malfunctions (Fig. 4e). At solar noon, the AES irradiance and the EPA irradiance are 4.8% apart. This systematic discrepancy between these two instruments existed throughout the intercomparison on both clear-sky and cloudy days. Discrepancies of this magnitude between the erythemal value measured by the different instruments were easily explained in 1994 and 1995 (e.g., wavelength registration). However, the cause of the discrepancy in 1996 is not due to any easily identifiable instrumental malfunctions or wavelength registration problems.

6. Calibration and data quality control of the UV broadbands

a. Data quality control and analysis

Figures 6a–f show the ratio of the particular YES UVB-1 radiometer to the average of the three YES instruments versus time for the CUCF's standard YES UVB-1 broadband radiometers that permanently reside at the TMTF. These results are for the clear-sky days during the three intercomparison campaigns. Figure 6 gives an indication of the stability of the YES UVB-1 radiometers over time. It is important to note that the potentiometer that determines the voltage output is never altered during these procedures. The three standard

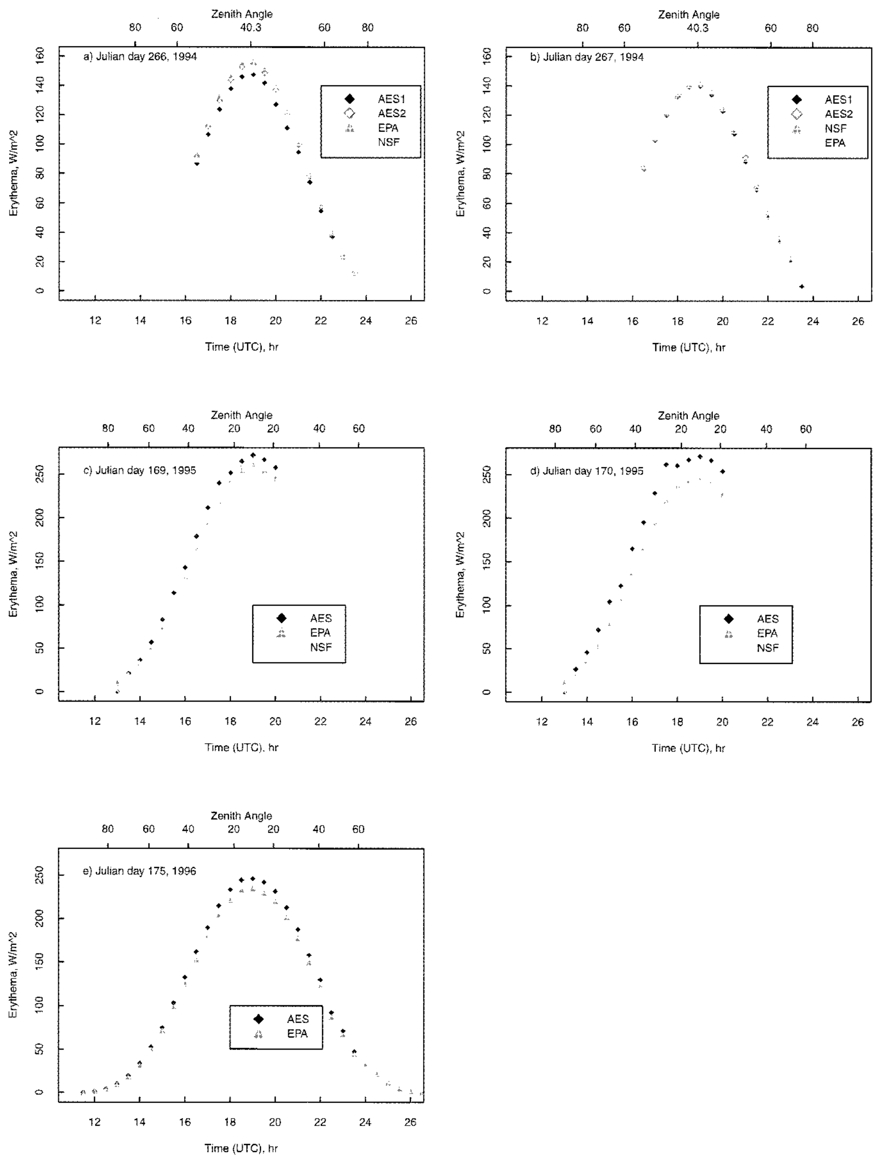

FIG. 4. The diurnal erythemally weighted spectroradiometer data from 280 to 400 nm for the clear-sky days during the first, second, and third North American Spectroradiometer Intercomparisons.

YES instruments were purchased in 1994 and during this period, as Figs. 6a–f show, the spread between the uncalibrated voltages of the three instruments has consistently been less than 2% from the mean for zenith angles less than 80°. This result clearly illustrates the temporal stability of the YES standard radiometers with respect to each other. DeLuisi et al. (1992) reached a similar conclusion with the spectral response function of the Robertson–Berger predecessor to the present meters. The asymmetry of the voltage signal in the YES instrument 940402 with zenith angle in Figs. 6a–f suggests an alignment problem with this particular instrument. This asymmetry is not evident in any of the other YES UVB-1 instruments, SL 501A instruments, or the spectroradiometers; therefore, the asymmetry is probably not due to atmospheric conditions, for example, mountains to the west, but is due to this particular instrument's characteristics. Even though the instrument base was mechanically leveled, it appears that the instrument is not optically level. The data from this instrument is not included in the calculation of the average calibration factors for the YES instruments. However, revelation of the errant instrument clearly illustrates the value of involving three (or more) standards.

The ''standard'' broadband radiometers from Solar Light, Inc. (SL 501A), were purchased in early 1996

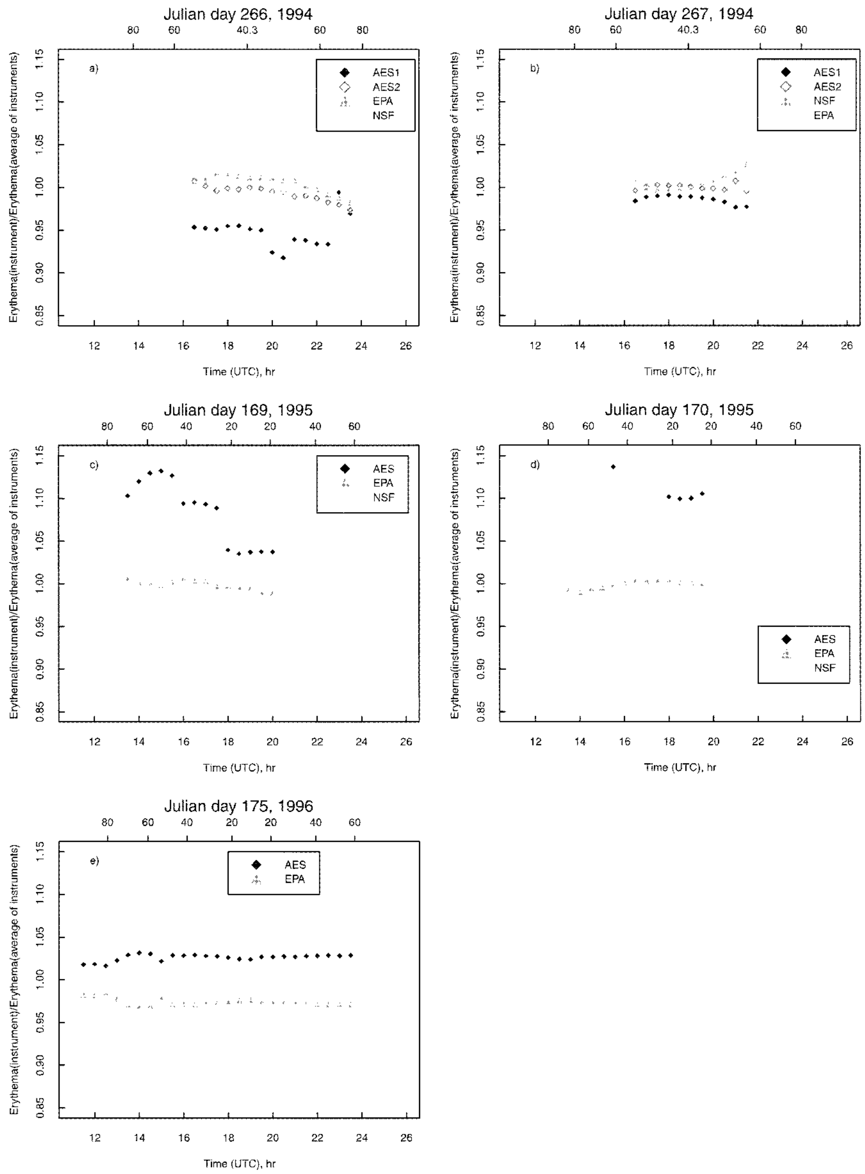

FIG. 5. The ratio of the erythemally weighted spectroradiometric data of each instrument to the average of the instrument. The average does not include the outliers, as indicated in the text.

and deployed during the third intercomparison. Therefore, there are no yearly values to assess their temporal stability with respect to each other, but the voltage output of these radiometers can be compared to the YES radiometers for the third intercomparison (Fig. 7). Figures 7a,b indicate that the three SL instrument are well behaved with respect to each other; that is, the spread between the instruments is less than 1.8%, which is similar to the YES radiometers. Figures 7c,d are the ratio of the normalized voltage signals of each instrument to the average of all six YES and SL broadband radiometers. These two figures show that the YES and SL radiometers each have their own distinct dependence on zenith angle where the differences in voltage readings reach 15% by a zenith angle of 80°. The following sections provides separate calibration factors as a function of solar zenith angle for the YES and SL UVB broadband radiometers.

b. Calibration factors

The erythemal clear-sky calibration factors [(W m^{-2}) mV^{-1}] for converting the voltage output of the UV broadband radiometers to an erythemally weighted irradiance value is calculated by dividing the erythemally weighted integrated spectroradiometric measurements

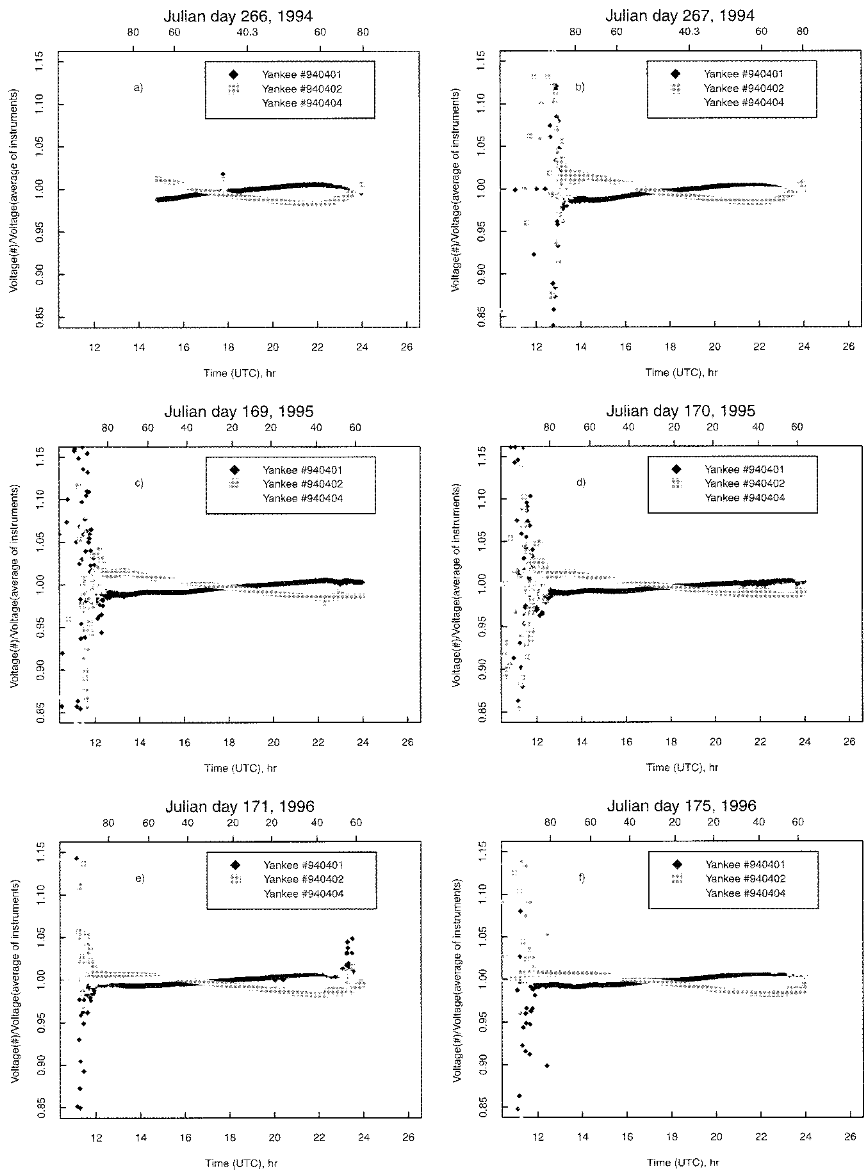

FIG. 6. The ratio of the voltage output of each of the Yankee broadband radiometers (YES UVB-1) to the average of the Yankee broadband radiometers.

corrected by the procedure described above by the 1-min average of 1-s UV broadband voltages for every half-hour across the day. Figure 8 gives the erythemal calibration factors as a function of zenith angle for the average of the two YES instruments for the two clear-sky days, where the error bars reflect the propagation of random uncertainties associated with the 1-min averaged UV broadband data, the average of the YES instruments, and the average of the spectroradiometric data. As expected the error bars for Julian day 175 1996 are large because of the unexpected large spread in the spectroradiometer data. The angular corrections of the spectroradiometer are not included in the erythema calibration factors in Fig. 8 and are placed in a separate table (see Table 1).

c. *Interannual changes in the erythemal calibration factors*

Calibration factors for the standard broadband radiometers are computed annually to take into account changes in their sensitivity from year to year. The erythemal calibration factors for Julian day 266 1994 and Julian day 170 1995 are compared (Fig. 9a). These particular days were chosen because they are both clear-sky days with total ozone concentrations that are similar with little ozone variability throughout the day (293.3 $\pm$ 1.2 D.U. and 292.4 $\pm$ 2.3 D.U.). The standard deviation in the average total ozone for these two days is approximately within two standard deviations of the individual measurements, which is on average 2.4 and 3.2

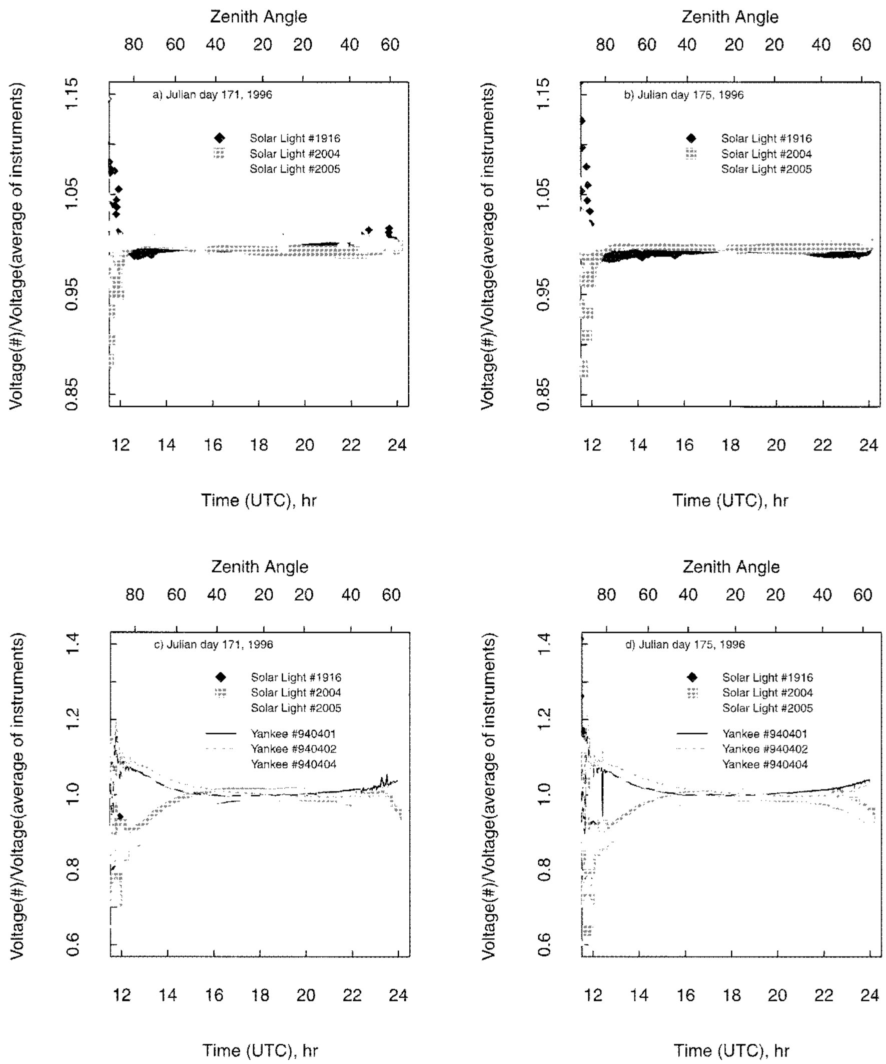

FIG. 7. Comparison of the diurnal voltage output of the Yankee broadband radiometer (YES UVB-1) to the Solar Light (SL) broadband radiometers (SL 501A) during the second intercomparison. (a) The ratio of the voltage output of each of the SL broadband radiometers to the average of the SL radiometers. The average does not include the outliers. (b) The ratio of the voltage output of each of the radiometers to the average of all six radiometers.

D.U. for days 266 and 170, respectively. In order to compare the two consecutive years, the erythemal calibration factors were fit with a cubic spline and interpolated to selected solar zenith angles. The ratio of erythemal calibration factors for the two years is plotted in Fig. 9b. Between zenith angles of 40° and 60° the calibration factors increased by approximately 2%–4%. These changes are just outside the random uncertainties of the measurements, but if one includes the systematic uncertainties these changes are within the total error. We are comparing the two years to assess the degree of change in the erythemal calibration factors. In general, an increase in the calibration factors could be due in part to decreases in the sensitivity of the broadband radiometer that could result from changes in the broadband's components, such as the spectral transmittance of the internal filters and the detector. It would be beneficial to compare measurements of the spectral response functions and cosine responses for these two years or to compare the absolute calibration factors, but information for this type of analysis was not acquired for this time period.

d. Synthesized erythemal calibration factors and atmospheric parameters

Even though the spectral response of the UV broadband radiometers was designed to mimic the erythemal spectral response, there are still notable deviations. Figure 1 shows that the erythemal skin response is more sensitive to longer (''redder'') wavelengths than is the typical UV broadband detector that cuts off more steeply

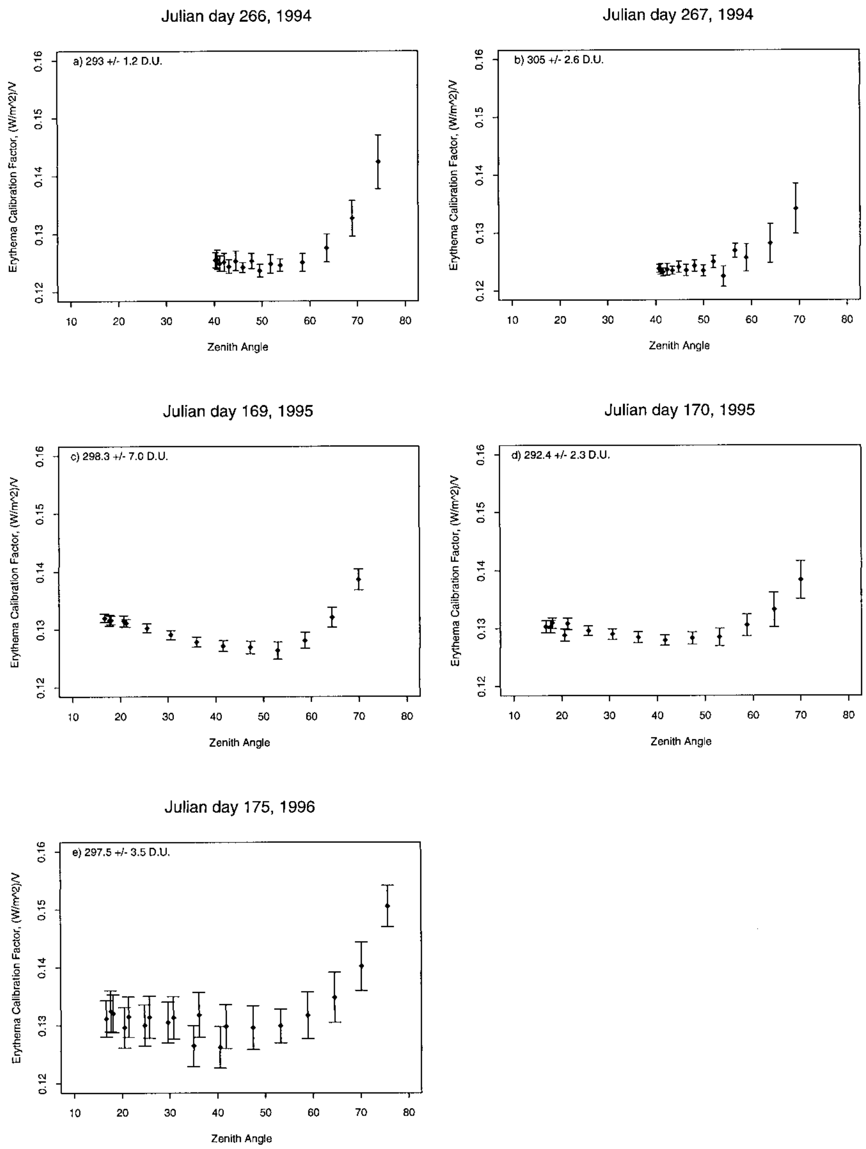

FIG. 8. The erythemal calibration factors (ECFs) for CUCF's YES UVB-1 standard radiometers from the first, second, and third intercomparisons. The error bars represent the random uncertainties associated with the average of the spectroradiometers and broadband data.

than the erythemal spectral response at wavelengths below 340 nm. These deviations mean that the erythemal calibration factors calculated above are dependent on any atmospheric parameter, which affects the wavelength distribution of the solar irradiance in this region. For the 280–400-nm region of the solar spectrum this is most notably solar zenith angle, total ozone, and Rayleigh scattering. Previous investigators (e.g., Mayer and Seckmeyer 1996) have calculated the zenith angle and ozone dependence for the erythemal calibration factors; however, we present the calculated values for completeness for users of the broadband data. The modeled erythemal calibration factors are determined using a discrete ordinates eight-stream radiative transfer model for an aerosol free atmosphere at 0 km (Stamnes et al. 1988) as a function of zenith angle and total ozone. The modeled erythemal calibration factors are determined by taking the ratio of erythema-weighted modeled irradiance that is integrated from 280 to 400 nm to the simulated voltage of the broadband radiometer, which is the modeled irradiance weighted with a representative spectral response function of each type of instrument (i.e., YES and SL) and integrated over wavelength. The erythemal calibration factors are modeled as a function of zenith angle and total ozone. The simulated voltage output, the denominator of the ratio, is determined using a typical spectral response function for the YES UVB-1 and the SL 501A broadband radiometer, as shown in Fig. 1 and

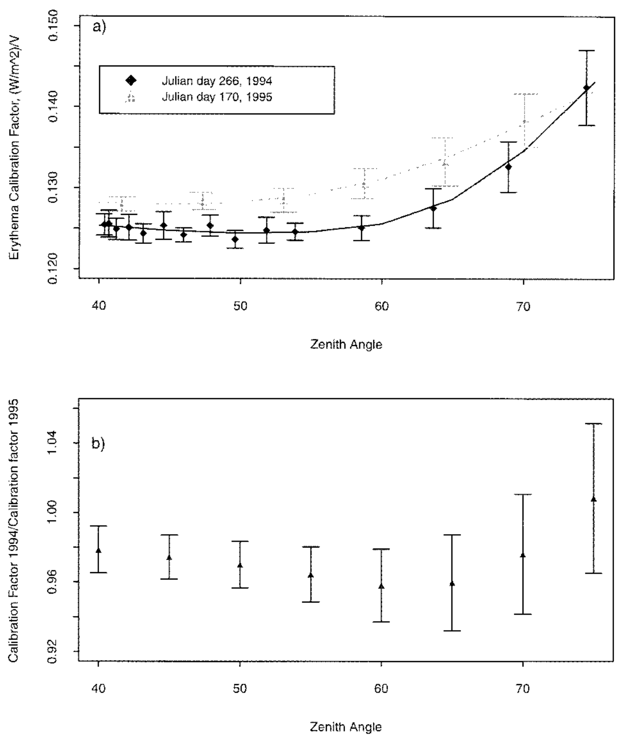

FIG. 9. (a) Erythemal calibration factors for Julian day 266 1994 and Julian day 170 1995. (b) Ratio of the erythemal calibration factors from Julian day 266 1994 to Julian day 170 1995. These two days were chosen because the total ozone was similar and relatively constant across the day (293.3 ± 1.2 D.U. and 292.4 ± 2.3 D.U., respectively).

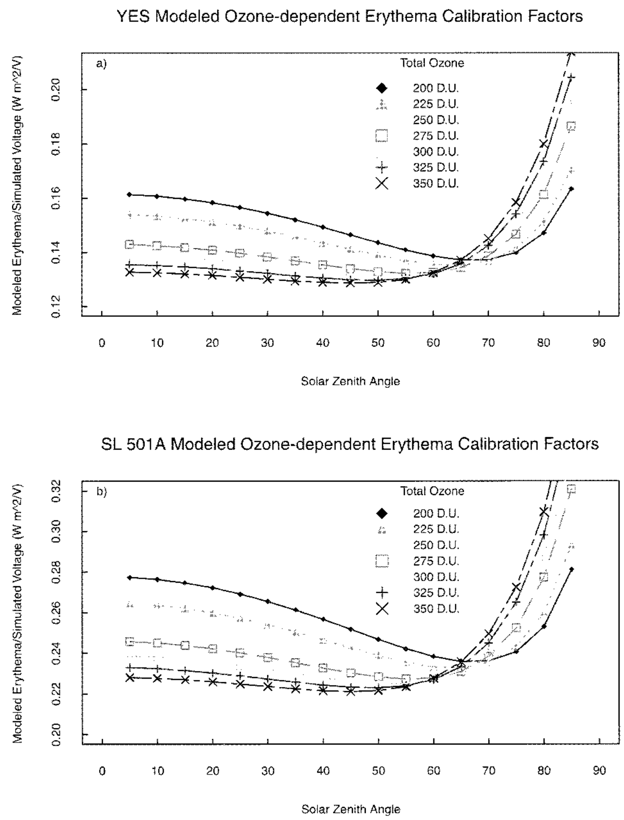

FIG. 10. (a) Modeled ozone-dependent erythemal calibration factors for the average of two standard YES UVB broadband radiometers (940401, 940404) normalized to the measurements from Julian day 170 and total ozone 292.4 D.U. (b) Modeled ozone dependent erythemal calibration factors for the standard SL 501A broadband radiometers (2005).

includes the cosine error of the UVB-1 broadbands as a function of zenith angle. The typical spectral response function of the YES UVB-1 and the SL 501A is based on the average of measurements determined by NIST (Thompson et al. 1997). The deviation of the response of the broadband radiometer from an ideal cosine response was determined at the CUCF for two planes, and the contribution of the cosine error to the simulated voltage was applied in a similar fashion as was described in section 5.3 for the spectroradiometer data. The YES modeled erythemal calibration factors are given in Fig. 10a and have been normalized to the measurements [0.1326 ± 0.001 (W m^{-2}) V^{-1}] at a zenith angle of 40° and 292.4 D.U. from Julian day 170 1995. The SL 501A modeled erythemal calibration factors are given in Fig. 10b and have been normalized to the measurements [0.2280 ± 0.005 (W m^{-2}) V^{-1}] at a zenith angle of 40° and total ozone of 297.5 D.U. from Julian day 175 1996. Tables 4 and 5 give the third-order polynomial fit to the ozone-dependent erythemal calibration factors for the average of CUCF's YES UVB-1 and SL 501A versus total ozone for various zenith angles.

As demonstrated in Figs. 10a,b total ozone has a significant effect on the calibration factors. As an example, this figure shows that uncertainties of approximately 15% would occur if one used a calibration factor for a zenith angle of 10° that was determined for a total ozone value of 350 D.U. when actual conditions were closer to 250 D.U. In addition, the same erythemal calibration factors are calculated with a surface elevation of 5 km to illustrate potential affects on the calibration factor if a network site has a different elevation than where the site at which the erythemal calibration factors are determined. The percent change in the erythemal calibration factors for a surface elevation change from 0 to 5 km is ±1.5% for solar zenith angles from 0 to 75. A check was performed to determine how well the modeled calibration factors compare with the measurements as a function of zenith angle. The modeled and measured YES calibration factors for Julian day 170 are compared in Fig. 11, where the modeled calibration factors have been normalized to the measured calibration factors at a zenith angle of 40°. The modeled erythemal calibration factors are determined for Julian day 170 using a discrete ordinates eight-stream radiative transfer model at 1.67 km (Stamnes et al. 1988) as a function of zenith angle. The modeled and measured calibration factors for day 170 agree to within 4% for zenith angles less than 60° (Fig. 11). The deviations between the modeled

TABLE 4. Ozone-dependent erythemal calibration factors (OECF (θ_0, Ω) [W m^{-2} V^{-1}]) for CUCF's triad YES UVB-1 from Julian day 169, 1995.

Zenith angle	OECFs (θ_0, Ω) = $a + bx + cx^2 + dx^3$ (x = total ozone, D.U.)			
	a	*b*	*c*	*d*
5	0.2922071	−0.0010700543	2.507783e-06*	−2.151118e-09
10	0.2909226	−0.0010659787	2.503954e-06	−2.149710e-09
15	0.2887926	−0.0010593770	2.498748e-06	−2.149068e-09
20	0.2857518	−0.0010495228	2.489950e-06	−2.146677e-09
25	0.2817053	−0.0010354213	2.474781e-06	−2.139631e-09
30	0.2765972	−0.0010165009	2.452310e-06	−2.127379e-09
35	0.2703120	−0.0009914065	2.418923e-06	−2.106077e-09
40	0.2627983	−0.0009594299	2.373653e-06	−2.075223e-09
45	0.2538458	−0.0009178972	2.308964e-06	−2.026392e-09
50	0.2433547	−0.0008650005	2.220457e-06	−1.954228e-09
55	0.2312924	−0.0007993653	2.106432e-06	−1.856559e-09
60	0.2176549	−0.0007193061	1.964954e-06	−1.729829e-09
65	0.2026103	−0.0006244508	1.801294e-06	−1.577609e-09
70	0.1864824	−0.0005154245	1.629020e-06	−1.412425e-09
75	0.1696917	−0.0003919890	1.465676e-06	−1.251410e-09
80	0.1534912	−0.0002531235	1.329457e-06	−1.113978e-09

* Notation to be read as 2.507783×10^{-6}, for example.

and the measured erythemal calibration factors with solar zenith angle could be due to a number of uncertainties in both calculations including uncertainties in the spectral response functions and cosine response functions of the broadband radiometers used in the modeled calculation, and uncertainties in the measurement of the angular error and its application to the spectroradiometric data used in the measured calibration factors. In the near future, the ozone-dependent ECFs will be determined experimentally using the U1000 spectroradiometer located at TMTF.

7. Conclusions

In this paper, we report our procedure for deriving clear-sky erythemal calibration factors as a function of solar zenith angle for the ''standard'' broadband radiometers residing at CUCF's TMTF (Fig. 8) and modeled erythemal calibration factors normalized to the measurements for the YES and the SL instruments as a function of solar zenith angle and total ozone (Figs. 10a,b). To convert the standard broadband radiometer's voltage output to erythemally weighted irradiance, mul-

TABLE 5. Ozone-dependent erythemal calibration factors (OECFs (θ_0, Ω) [W m^{-2} V]) for CUCF's triad SL 501A from Julian day 175, 1996.

Zenith angle	OECFs (θ_0, Ω) = $a + bx + cx^2 + dx^3$ (x = total ozone, D.U.)			
	a	*b*	*c*	*d*
5	0.3532122	−8.728552e-04*	2.009733e-06	−1.629419e-09
10	0.3526528	−8.736726e-04	2.021149e-06	−1.642503e-09
15	0.3517275	−8.752238e-04	2.041552e-06	−1.666259e-09
20	0.3503207	−8.763259e-04	2.067561e-06	−1.697020e-09
25	0.3483269	−8.760033e-04	2.097177e-06	−1.733063e-09
30	0.3456654	−8.735478e-04	2.129932e-06	−1.774787e-09
35	0.3421238	−8.666825e-04	2.160184e-06	−1.816506e-09
40	0.3375685	−8.539955e-04	2.186283e-06	−1.857697e-09
45	0.3315995	−8.307619e-04	2.195569e-06	−1.884955e-09
50	0.3239760	−7.936056e-04	2.181177e-06	−1.891575e-09
55	0.3144448	−7.384240e-04	2.135536e-06	−1.870394e-09
60	0.3027311	−6.597676e-04	2.048054e-06	−1.809885e-09
65	0.2888240	−5.539811e-04	1.918687e-06	−1.711255e-09
70	0.2729288	−4.182981e-04	1.756649e-06	−1.588204e-09
75	0.2557100	−2.521254e-04	1.585434e-06	−1.477528e-09
80	0.2387481	−5.221696e-05	1.407098e-06	−1.401641e-09
85	0.2291935	1.625793e-04	1.197029e-06	−1.330175e-09

* Notation to be read as -8.728552×10^{-4}, for example.

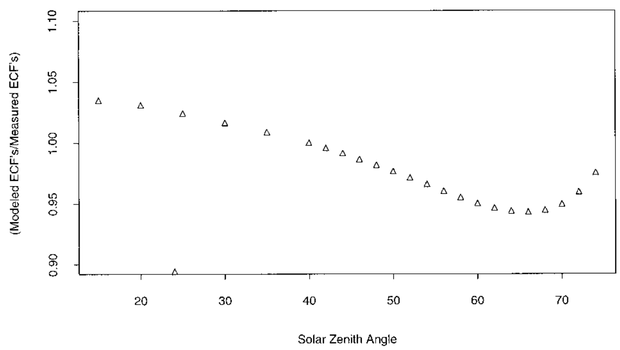

FIG. 11. Ratio of the modeled and measured erythemal calibration factors for the YES UVB-1 standard radiometers as a function of zenith angle for Julian day 170 and total ozone 292.4 D.U.

tiply the instrument's voltage by the clear-sky erythemal calibration factor given in Fig. 10 at the appropriate zenith angle and total ozone in D.U., and then multiply by the spectroradiometer cosine correction factor at the same zenith angle given in Table 1. Therefore, if the YES UV broadband voltage was 1.220 V at a solar zenith angle of 40° and the total ozone for that day was 292.4 D.U., then the erythemally weighted irradiance will be (1.220 V)(0.1272 (W m^{-2})/V)1.041 = 0.161 W m^{-2}. Alternatively, for any given day with a known total ozone value, the erythema-weighted irradiance from the voltage output of CUCF's YES UVB-1 standard radiometers can be determined using the fitted equations given in Table 4. The polynomial fit includes the cosine correction for the spectroradiometer data. The relative standard deviation due to random uncertainties in the spectroradiometer and broadband measurements for the reported erythemal calibration factors is ±2%; systematic uncertainties include ±2% in the irradiance transfer for the NIST lamp, ±2.8% in the cosine corrections to the spectroradiometer, which results in a total uncertainty of ±4% for a clear-sky erythemal calibration factor.

The above description gives an example of how to convert the voltage output from the standard broadband radiometers to an erythemal weighted irradiance, but these numbers are specifically for these standards. Each UV broadband radiometer of the various UV monitoring networks will pass through the CUCF's laboratory and the TMTF once per year, whereas the broadband radiometers of a network will be compared with the standard broadband radiometers, and erythemal calibration factors will be determined at a given total ozone as a function of solar zenith angle. Using these erythemal calibration factors numbers for instruments other than the standards will cause an additional error of approximately 2%–7% from 0° to 75° solar zenith angles. This is based on results of calibrated sets of SURFRAD network broadband radiometers that have passed through the CUCF.

The modeled calibration factors as a function of ozone illustrate the importance of total ozone in determining the calibration factor. This means that either the UV monitoring network needs to supply the total ozone for that day and site or should mention that the user will need to correct the data using satellite ozone data. Either way the user of the data will need to be made aware of the error induced by not taking into account the ozone correction to the conversion from volts to erythemally weighted irradiance. As this paper has highlighted, ozone is not the only parameter that affects the erythemal calibration factor and the true erythemal calibration factor is dependent on any parameter that affects the spectral distribution of UV irradiance. However, these parameters are expected to have less of an effect than ozone and zenith angle. Surface elevation was an example of such a parameter but as the example illustrated using a calibration factor determined at sea level on data obtained at a surface elevation of 5 km would cause only a 1%–2% error in the conversion to erythemally weighted irradiance. Certainly, there are other factors that contribute to the error of the conversion of the broadband output to erythemally weighted irradiance. These include wavelength-dependent albedo, ozone altitude profiles, or wavelength-dependent aerosol optical effects. Differences in the erythemal spectral response function and the spectral response function of a given type of instrument add to the uncertainties of erythemal irradiance determined from broadband radiometers and lengthen the time required to determine trends (Weatherhead et al. 1997). This suggests that UV trends from broadband radiometers may be better determined using instrument calibration factors that use the instrument's spectral response function. However, these will indicate only trends observed within a given type of broadband instrument. Another important point to mention is that these erythemal calibration factors are for clear skies. There is expected to be some variation in the calibration factors with the degree of cloudiness and aerosol content of the atmosphere, in part because of the differences in cosine responses of the spectroradiometer and broadband instruments. In essence, anything that may affect the distribution of sky radiance will also effect the erythemal calibration factor. Last, this work illustrates the necessity of having two to three spectroradiometers and two to three broadband instruments to intercompare the data and check for inconsistencies in the data.

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