All-weather calibration of broadband (Robertson-Berger type) meters for ozone dependency

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Broadband solid-state detectors, which are robust, relatively inexpensive and uncomplicated to operate, are particularly suitable for routine measurements of biologically damaging solar ultraviolet-B (UV-B: 280–320 nm) radiation, especially in developing countries with limited financial resources and human technical capacity. Specific tables of conversion factors provided by manufacturers of these instruments correct for their dependence on solar zenith angle (SZA) but not on total column ozone; this dependence is due to slight wavelength mismatches between the instruments' spectral responses and biological action spectra. An entirely instrument-based calibration procedure has been described but is applicable only at sites with clear skies and abnormally low atmospheric pollution. We have investigated the practicality of calibrating such equipment customarily operating under all weather conditions with typical atmospheric pollution by comparing satellite observation of total column ozone with simultaneous broadband pyranometer and spectroradiometer measurements of erythemal-weighted solar UV-B irradiance over a 42-month monitoring period. The numerous (2657) measurements taken were inadequate to quantify, within statistically acceptable limits, the divergence of ozone-related observations by pyranometer and spectroradiometer of UV-B irradiance at different solar zenith angles. However, a general linear regression that quantified differences in UV-B irradiance measured by broadband instruments as a function of total column ozone inclusive of all SZA values conformed to statistically acceptable criteria. Application of the regression slope and intercept coefficients in a remedial equation reduced the total number of broadband instrument errors in measurement of UV-B irradiance by 40% but by small margins only; these averaged 2.40 ± 0.44%. The considerable time and expenditure entailed for such small corrections are not readily justified.

Introduction

Since the discovery of stratospheric ozone depletion, scientists have become concerned about what effects increased solar ultraviolet-B (UV-B) radiation observed in the troposphere of both the southern and northern hemispheres[1,2] has on the earth's biota.[3] These concerns are especially pertinent to the southern hemisphere, where stratospheric ozone destruction is more intense,[4] and solar UV-B fluxes are up to 50% greater than those at comparable latitudes in the northern hemisphere.[5] Scientists studying these effects need reliable ground-based measurements of solar UV-B flux and several dosimeter networks have been established worldwide.[6,7]

Broadband solid-state detectors, which are robust, relatively inexpensive and uncomplicated to operate, are widely used for routine measurements of biologically damaging UV-B irradiance,[8] especially in African countries with limited resources and human technical capacity.[9] Several commercial versions of the popular Robertson-Berger (R-B) type of meter[10] are available and their spectral characteristics are somewhat similar to each other. The manufacturers of these instruments provide conversion factors for estimating various parts of the UV-B spectrum (280–315 nm or 280–320 nm) and weighted integrals according to various biological action spectra, for example, the International Commission for Illumination (CIE) reference action spectrum,[11] and the Parrish action spectrum.[12]

There are several reports on the absolute calibration of R-B type meters, including detailed theoretical assessments of these instruments.[13–15] All of these reports compare broadband UV measurements with a co-located spectroradiometer whose spectra are weighted with equivalent erythemal or other biological action spectra integrated over the wavelength response range of the broadband instrument. These comparisons have shown that the responses of broadband instruments are influenced by solar zenith angle (SZA) and total column ozone. SZA reliance is due to the cosine dependence of horizontal incidence-type sensors, altered proportions of direct and diffuse radiation at different angles, and variation in these partly with wavelength. Ozone reliance is due to wavelength mismatches between broadband instrument spectral responses and biological action spectra, for example, displacement of some broadband spectral responses to slightly longer wavelengths in the steep fall-off region of biological action spectra.[15]

An entirely instrument-based procedure for calibrating a reference broadband instrument and transfer of the calibration to other broadband instruments of the same type has been described.[15] It is noteworthy that the calibration constants presented for different SZAs and total column ozone were obtained at a site under clear skies at an altitude of 3400 m with abnormally low atmospheric pollution.[15] The practicality of calibrating such equipment customarily operating under all weather conditions at lower altitude in the presence of typical atmospheric pollution is uncertain, and was investigated in the study reported here.

Methods

Ozone measurements. Measurements of total column ozone were obtained from the NASA Total Ozone Mapping Spectrometer (TOMS) instrument flown on board the Nimbus 7,[16] Meteor 3,[17] Earth Probe[18] and Adeos[19] satellites, and also from the Global Ozone Monitoring Experiment (GOME) on the ERS-2 satellite.[20] Ozone values in Dobson units (DU) over Durban (29°58'S, 30°57'E) were extracted from 1° latitude by 1.25° longitude satellite grid data using bilinear interpolation. Owing to the different satellite orbits, sampling close to local midday was every 24 hours for TOMS and every 72 hours for GOME.

Solar ultraviolet-B measurements. Concurrent measurements of solar UV-B flux were obtained with broadband and narrowband instruments located on top of an observation tower, which allowed an unobstructed view of the horizon, at the University of Natal in Durban. The broadband instrument was an internally temperature-stabilized pyranometer (YES model UV-B1, Yankee Environmental Systems Turners Falls, MA, U.S.A.) operated in accordance with the manufacturer's instructions,[21] and calibrated against an unused reference YES pyranometer at approximately six-monthly intervals. The instrument's analogue voltage output was interfaced with a data logger which

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digitized and averaged readings recorded every 15 s over 5-min intervals. The effective South African Standard Time (SAST) of each averaged analogue voltage reading was assigned to the centre of the 5-min recording interval. Averaged voltage readings were downloaded daily into a personal computer programmed to compute the corresponding SZA and to convert voltage readings into absolute and biologically weighted (280–320 nm) irradiances compliant with the CIE reference erythemal action spectrum.[11]

The narrow-band instrument was a double monochromator spectroradiometer (Bentham model DM 150, Bentham Instruments, Reading, Berkshire, U.K.) interfaced with a personal computer. The instrument's stepper-motor-driven gratings covered the spectral range 290–500 nm with a band width of 1 nm and a scan time of 180 s. The light sensor was a fibre-optic cable topped by a teflon diffuser connected to a temperature-stabilized photomultiplier detector sealed in an insulated container. The instruments were calibrated monthly. Absolute response was checked against an incandescent lamp (Bentham CL2, Bentham Instruments) mounted inside a baffled cylinder to exclude ambient and reflected lamplight. Wavelength alignment was checked against vapour emission lines from a mercury arc lamp. The spectroradiometer was programmed to start measurements at dawn and perform scans at intervals of 5-degree SZA throughout the day. Absolute spectral irradiance measurements were biologically weighted with the CIE reference erythemal action spectrum[11] and integrated over the range 280–320 nm. Standard times (SAST) were assigned to the centre of the effective wavelength of the integrated spectra.

Data synthesis and statistical analysis. Measurements of erythemal UV-B irradiance using the pyranometer and spectroradiometer during the course of each day were matched for date, SAST and SZA. The criteria applied in selecting suitably paired irradiance measurements were that the effective standard times and corresponding SZA assigned to the corresponding individual irradiances deviated by no more than 60 s in duration and 0.25° in SZA.

Paired spectroradiometer [S(CIE)] and pyranometer [S(UV-B1)] measurements of erythemal UV-B irradiance were tested for concordance according to recommended statistical procedures for comparing two methods (instruments) of measurement.[21] Instrumental comparisons were restricted to those paired measurements taken at 09:00, 12:00 (solar noon) and 15:00 SAST only, which adequately sampled the SZA range of 6–70° over the 42-month (November 1996 to April 2000) monitoring period. In order to obtain realistic numbers of independent samples for statistical comparison, the differences in measured erythemal UV-B irradiance were grouped into 32 different SZA × ozone categories, that is, 8 × 8° SZA against 4 × 25 DU. In each category, the differences in irradiance between instruments were plotted against the sums of the measurements. A Student's *t*-test assessed the null hypothesis that the mean differences between instruments were zero.[21] A computed Pearson correlation coefficient tested for significant instrumental bias, that is, to check whether one instrument gave higher or lower values than the other.[22] Although statistical tests were conducted on absolute instrumental differences, the differences were also displayed as percentages, that is, [S(UV-B1 – S(CIE)] × 100/S(CIE), so that their magnitude and propensity were explicit. Ordinary least regressions of S(UV-B1)/S(CIE) ratios against total column ozone quantified the divergence of pyranometer from spectroradiometer measurements of UV-B irradiance in the eight different SZA categories. Student's *t* tested the statistical significance of the regression slope and intercepts. Statistically significant slope and intercept coefficients were used in the following remedial equation to correct the pyranometer-based measurements of irradiance:

$$S(\text{UV-B1})_{\text{corrected}} = \frac{S(\text{UV-B1})_{[illegible]}}{(\text{Slope coefficient} \times \text{Ozone value} + \text{Intercept coefficient})} \quad (1)$$

Differences between the ozone-corrected measurements of UV-B irradiance [$S(\text{UV-B1})_{\text{corrected}}$] and the corresponding S(CIE) measurements were re-tested for statistical significance and bias according to the procedures described above, and compared with the original S(UV-B1) – S(CIE) differences, which excluded an ozone correction.

Results and discussion

The 1277-day monitoring period included only 2657 properly paired pyranometer and spectroradiometer measurements, a consequence of incomplete ozone coverage by satellite (177 days), and of calibration and performance checks on the pyranometer (31 days) and spectroradiometer (178 days). Erythemal UV-B irradiances measured by both instruments displayed proportionately similar decreases with increasing total column ozone in all SZA categories, except in the range 6–13° (Fig. 1). Statistically significant differences in the corresponding instrument readings were apparent in 12 (40%) of the 30 SZA × ozone categories (Fig. 1). These were most common in the presence of moderately low total column ozone (251–275 DU), when the pyranometer significantly ($P \leq 0.05$) underrated UV-B irradiances by as much as –9.0 ± 3.7%. These underrated irradiances by the broadband instrument were evident in all SZA categories, except 55–62° and 63–70° (Fig. 1). Conversely, with high total column ozone (301–325 DU), the pyranometer significantly ($P \leq 0.05$) overrated erythemal UV-B irradiances by as much as 12.2 ± 4.8%, but these were evident in only the SZA categories 22–29°, 30–37° and 46–54° (Fig. 1). These trends, however, were

Table 1. Statistics for regressions of total column thickness against measured pyranometer/spectroradiometer [S(UV-B1)/S(CIE)] ratios of erythemal UV-B irradiance for different categories of solar zenith angle (SZA)

SZA category	r	Regression intercepts S(UVB1)/S(CIE) constant	*t*-statistic	Significance level (P)	Regression slopes Ozone coefficient	*t*-statistic	Significance level (P)
63–70°	0.0011	**0.9592**	**$t_{1,346} = 3.9976$**	**0.0009**	0.0007	$t_{[illegible]} = 0.6089$	0.5430
55–62°	0.0020	0.8587	**$t_{1,344} = 4.1243$**	**<0.0001**	0.0006	$t_{[illegible]} = 0.8298$	0.4073
46–54°	0.0208	**0.4681**	**$t_{1,662} = 3.3247$**	**0.0009**	**0.0019**	**$t_{1,662} = 3.7470$**	**0.0002**
38–45	0.0029	**0.6682**	**$t_{1,319} = 3.1792$**	**0.0015**	0.0011	$t_{[illegible]} = 1.4420$	0.1497
30–37°	0.1254	–0.4446	$t_{[illegible]} = -1.2339$	0.2198	**0.0052**	**$t_{1,112} = 4.0068$**	**0.0001**
22–29°	0.0242	0.3989	$t_{[illegible]} = 1.2098$	0.2287	0.0021	$t_{[illegible]} = 1.7395$	0.0845
14–21°	0.0266	0.1782	$t_{[illegible]} = 0.4198$	0.6754	0.0029	$t_{[illegible]} = 1.8623$	0.0649
6–13°	0.0001	0.9247	$t_{[illegible]} = 1.7579$	0.0802	0.0002	$t_{[illegible]} = 0.1177$	0.9064
6–70°	0.0033	**0.7455**	**$t_{1,2655} = 8.3519$**	**<0.0001**	**0.0010**	**$t_{1,2656} = 2.9491$**	**0.0032**

Significant regression and slope intercepts presented in boldface.

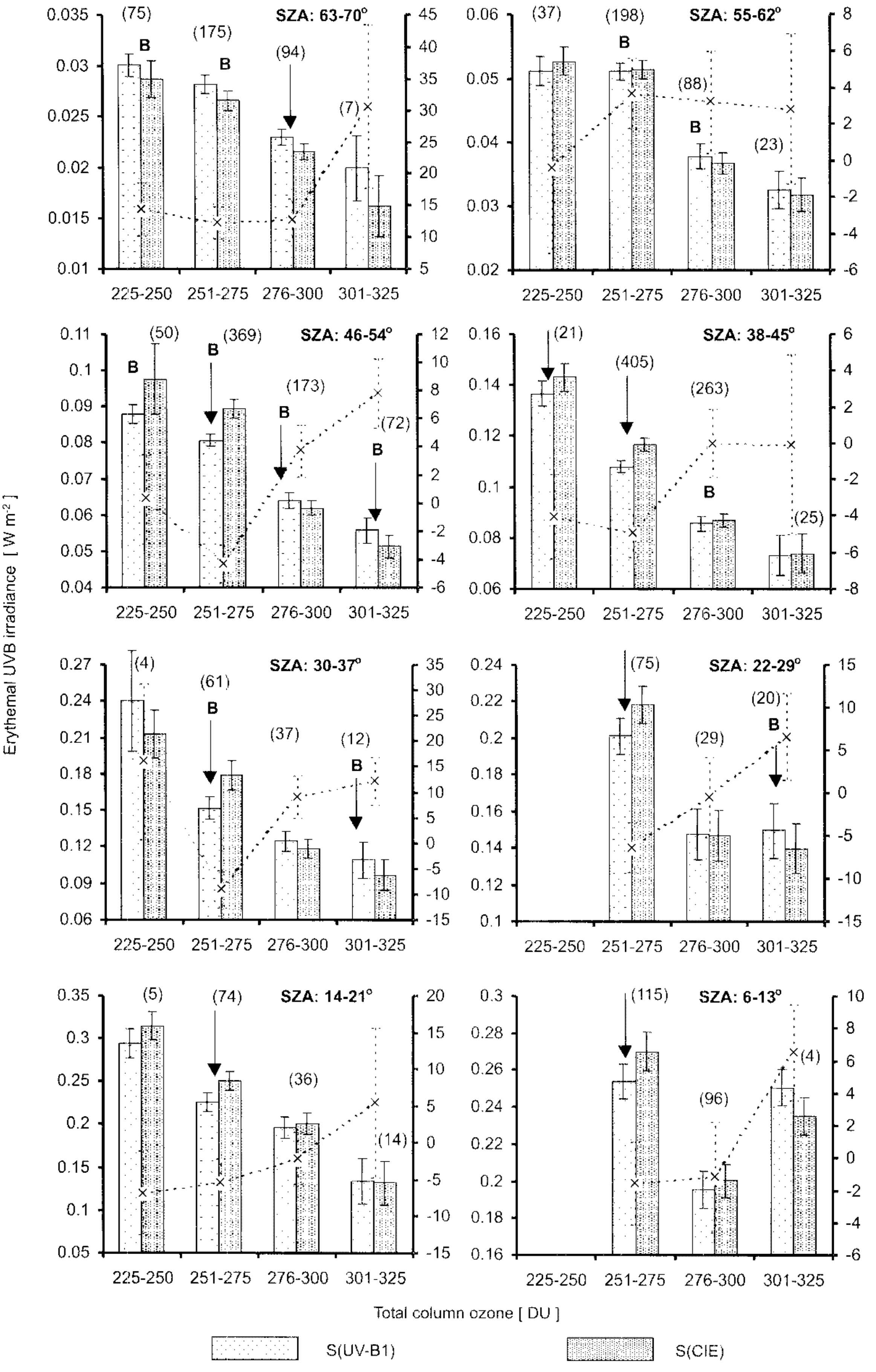

Fig. 1. Pyranometer [S(UV-B1)] and spectroradiometer [S(CIE)] measurements of erythemal UV-B irradiance, including percentage divergence ± standard errors for different categories of solar zenith angle (SZA) and total column ozone. Numbers of paired measurements presented in brackets. Significant ($P \leq 0.05$) instrument differences indicated by an arrow and bias by the letter B.

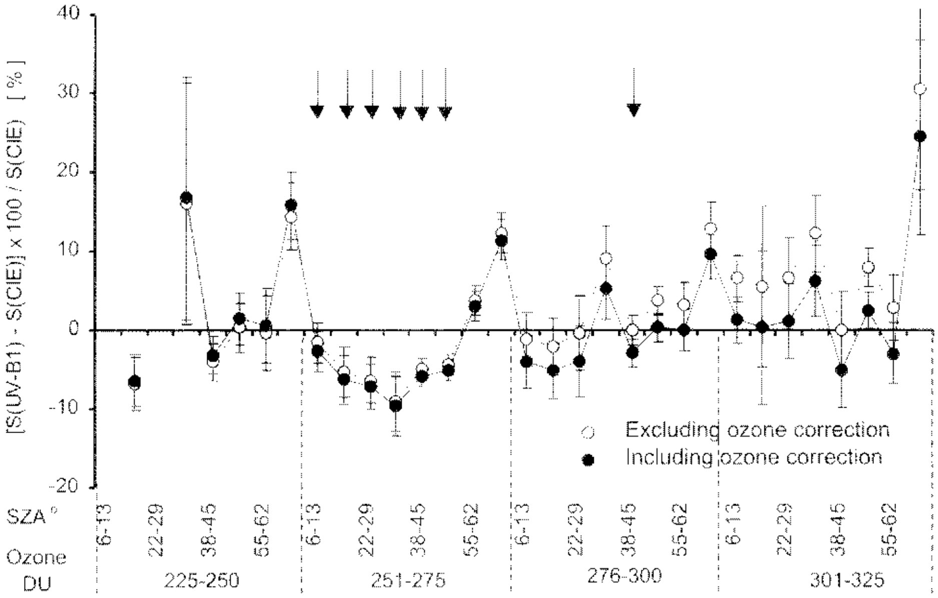

Fig. 2. Percentage divergence ± standard errors of pyranometer [S(UV-B1)] from spectroradiometer [S(CIE)] measurements of erythemal UV-B irradiance for different categories of solar zenith angle (SZA) and total column ozone. Significant ($P < 0.05$) instrument differences indicated by arrows of different shading intensity for measurements excluding (grey) and including (black) corrections for ozone dependency.

not readily quantified. Ordinary least-squares regressions of S(UV-B1)/S(CIE) ratios against total column ozone displayed statistically significant slope and intercept coefficients only in the SZA range 46–54° (Table 1). This contrasted with the significant linear relationships observed between these ratios and total column ozone over a wide range of SZA values at a site with clear skies and abnormally low atmospheric pollution.[15] Nevertheless, where our measured S(UV-B1)/S(CIE) ratios, inclusive of all SZA values, were plotted against total column ozone, a linear regression with both significant slope and intercept coefficients was obtained (Table 1). Incorporation of these coefficients in the remedial equation reduced the total number of significant differences in corresponding instrument measurements by 40% but by small margins only; these averaged 2.40 ± 0.44% (Fig. 2).

In conclusion, our observations indicate that the calibration of broadband detectors for ozone dependency at precise SZA values is unrealistic for such instruments customarily operating under all weather conditions. Indeed, scattering of UV radiation by atmospheric aerosols and cloud adds substantially to the overall variance in instrumental measurements, precluding the derivation of statistically meaningful calibrations. Nevertheless, limited calibration of broadband instruments is feasible but the considerable time and expenditure entailed for the small corrections obtained are not readily justified.

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