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Temperature dependence of the Brewer ultraviolet data

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Abstract. We characterize the temperature dependence of the U. S. Environmental Protection Agency/University of Georgia network of Brewer spectrophotometers as used to measure solar ultraviolet (UV) radiation. The instruments used in this study are operated in partnership with the National Park Service at 14 national park sites and in 7 urban areas. The daily and seasonal measurements of UV radiation provided by the instruments can be affected by changes in the internal instrument temperatures at the sites. These effects can lead to errors on the order of ±10% in the resulting spectral data and of the same order of magnitude for CIE-weighted UV. Fortunately, the temperature dependence for each instrument can be quantified and the data corrected, improving the accuracy to values closer to the levels attainable with high-quality calibration and operation. The temperature dependence of the Brewers is found to vary significantly among the different instruments. A 0.8% per degree Celsius dependence can result in temperature effects as large as 12% at sites where temperatures can vary by 15°C in 1 day. These effects can result in a ±5% error in the spectral irradiance. The errors to the spectral irradiance vary seasonally in a manner that is not random: in the warmer summertime the temperature dependence of the instruments can cause the irradiances to be underestimated, while during the colder winters the effect will be to overestimate UV amounts. In the part of the spectrum above 325 nm, the temperature dependence is generally independent of wavelength. Below 325 nm the temperature effects vary as a function of wavelength over a range of values and are generally largest at the shortest wavelengths. Because changes in temperature from one calibration to the next can affect an instrument's response, understanding the temperature effects is necessary to ensure that artificial trends are not introduced into the Brewer data records.

1. Introduction

This paper describes the temperature characterizations and resulting corrections to both spectral irradiance and CIE-weighted UV for the 21 Brewer instruments comprising the U.S. Environmental Protection Agency (EPA)/University of Georgia (UGA) UV network. Operated in partnership with the National Park Service (NPS), the instruments comprise the largest Brewer UV network in the world. The instruments are located in diverse sites across the United States, including 14 national parks from as far north as Denali National Park (63.7°N) in Alaska to as far south as Virgin Islands National Park (18.3°N).

Brewer spectrophotometers have been used to measure the ultraviolet (UV) part of the solar spectrum for over a decade. The techniques for measuring global ultraviolet radiation are described in a number of references, including *Josefsson* [1992] and *Kerr* [1985]. The instruments were originally designed for total column ozone measurements. These measurements are usually corrected for effects due to changes in temperature, which has therefore meant that the instruments are not generally temperature stabilized. Because the ozone algorithms are based on ratios, temperature-related changes to the instrument response are not critical as long as the changes are independent of wavelength. The spectral measurements of UV irradiance, however, can be directly affected by changes in temperature.

The Brewer instruments at 21 EPA/UGA and NPS monitoring sites are Brewer MKIV spectrophotometers. The instruments are described in greater detail by *Kerr* [1985] but essentially contain a modified Ebert f/6 monochromator to measure column ozone, UV-A (320–400 nm), and UV-B (290–320 nm) radiation over a wavelength range from 286.5 to 363 nm. This wavelength range has been expanded from that of previous MKIVs to measure further in the UV-A spectrum. Although the Brewers are not temperature stabilized, each is equipped with a heater that when connected is automatically activated to warm the instrument if the temperature falls below 9°C. In general, the internal temperatures of an instrument can vary from a few degrees to more than 40°C.

As part of the routine maintenance of the network instruments, a 50 W quartz tungsten halogen lamp is periodically placed over the UV dome and diffuser assembly of each Brewer instrument and scanned in wavelength. This external lamp test helps measure any changes to the instrument re-

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sponse over time. At some sites the scans may be performed as often as twice monthly; at others they may be completed only a few times per year. Because these tests are performed throughout the year and cover a range of temperatures, the data provide an opportunity for estimating the temperature dependence of the instruments.

Fortunately, the temperature dependences of the Brewer instruments can be corrected once their nature is understood. The instrument internal temperature sensors, one of which is located near the photomultiplier tube, provide information on the temperature at which each scan is performed, and the routine external lamp tests provide data relating to the instrument response. In this study we use the data provided by the routine external lamp tests to examine and characterize the temperature dependences. We also report the magnitudes of the temperature effects on measured spectral irradiances and on the Commission Internationale de l'Eclairage (CIE) weighted daily dose.

2. Methods

Several methods have been investigated to obtain temperature characterizations for the Brewer instruments. Our results rely on information from external lamp tests, run routinely at the sites. Another approach is to utilize information from the internal lamp. These methods are complementary and offer unique advantages.

Cappellani and Kochler [2000] present their results for the temperature dependence of Brewer 066 using external lamp information. They report no ambient temperature effects on the spectral irradiance of the external lamps, similar to work reported by *Gillotay* [1997]. Laboratory tests indicate a significant temperature dependence of these lamps, however, affecting the response on the order of 0.05 to 0.1% per °C [*Meltzer et al.*, 2000].

Meltzer et al. [2000] tested the Brewer temperature responsivity using a calibrated 1000 W FEL lamp in the laboratory. The lamp was operated at a constant current in a controlled temperature environment, while the temperature of the Brewer was adjusted from −18° to +42°C in a separate temperature-controlled environment. These laboratory tests provide a rigorous and robust method for determining the temperature dependence of the lamp and Brewer independently. Work is under way to develop more accurate laboratory and field characterizations of all of the Brewer instruments in the EPA/UGA network. Procedures are currently being developed to conduct external lamp tests at each of the field sites using a laboratory-tested lamp at a constant current. This constant current is provided by a regulated DC power source whose output is kept constant by monitoring the voltage across a low-resistance standard resistor in a series with the lamp [*Meltzer et al.*, 2000]. If the resistor and voltmeter have temperature coefficients that are negligible or can otherwise be accounted for, the remaining temperature dependence of the signal will be due to the Brewer instrument and to the regulated external lamp. The results of these tests will provide additional information to complement the findings presented here.

Internal lamp information is maintained by each Brewer instrument and was tested for usefulness in quantifying the temperature dependence. For some instruments, use of this internal lamp information provides results consistent with the external lamp tests. The change in response with increasing temperature for Brewer 101 at Boulder, Colorado, is shown in Figure 1. The data, taken from the internal lamp scans, show a decrease in instrument counts as temperature increases. The decrease appears to be largely linear over the range of temperatures recorded by the Brewer instrument. Our ability to develop reliable temperature corrections from the internal lamp data was limited, however, both by inconsistencies in the data and by the lack of information on the temperature dependence of the internal lamps.

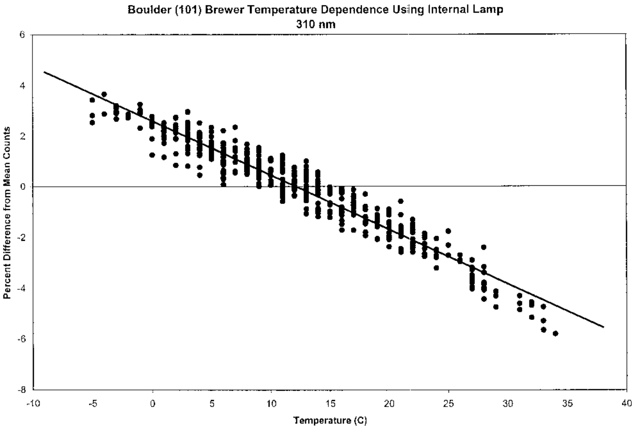

Figure 1. Difference in mean counts as a function of temperature for the internal lamp of Brewer 101 (Boulder, Colorado). The counts decrease linearly as temperature increases, corresponding to a similar response observed using external lamp data. The data were collected from Julian day 027 to Julian day 151 of the year 2000.

For this study we use the data provided by the external 50 W quartz tungsten halogen lamp tests performed at each of the sites. Testing with these external 50 W calibrated lamps can provide estimates of the temperature dependence for individual instruments, but the tests must be run on a significant number of days to fully capture the range in temperatures that may occur at a site. We rely on the 50 W external lamp tests performed at time intervals from twice monthly to once per season or less at each of the Brewer sites. The lamps are supplied by Kipp and Zonen, the instrument manufacturer. When these tests are performed frequently enough, they provide a fair amount of information for each site and can help determine the instrument stability over a range of temperatures. Because the tests are run in situ, they capture a representative range of temperature variations at each site.

2.1. Site Temperature Differences

Ambient temperature fluctuations at the EPA/UGA and NPS sites can span a large range. Denali can experience a mean maximum temperature of almost 19°C in July and a mean minimum temperature of −24°C in January. Even at midlatitude sites, the seasonal variations in temperature can be on the order of 15°C or more. These changes in ambient temperature directly affect the internal temperature of the Brewer instruments.

Figure 2a shows the ambient versus internal temperatures for Brewer 133 at Canyonlands National Park. The Brewer's aluminum casing limits air circulation, allowing the instrument to heat at a greater rate than the surrounding air. The Brewer instruments are heated radiatively as well as convectively. This heating can vary from day to day and from site to site, with instruments at higher altitudes generally subject to greater

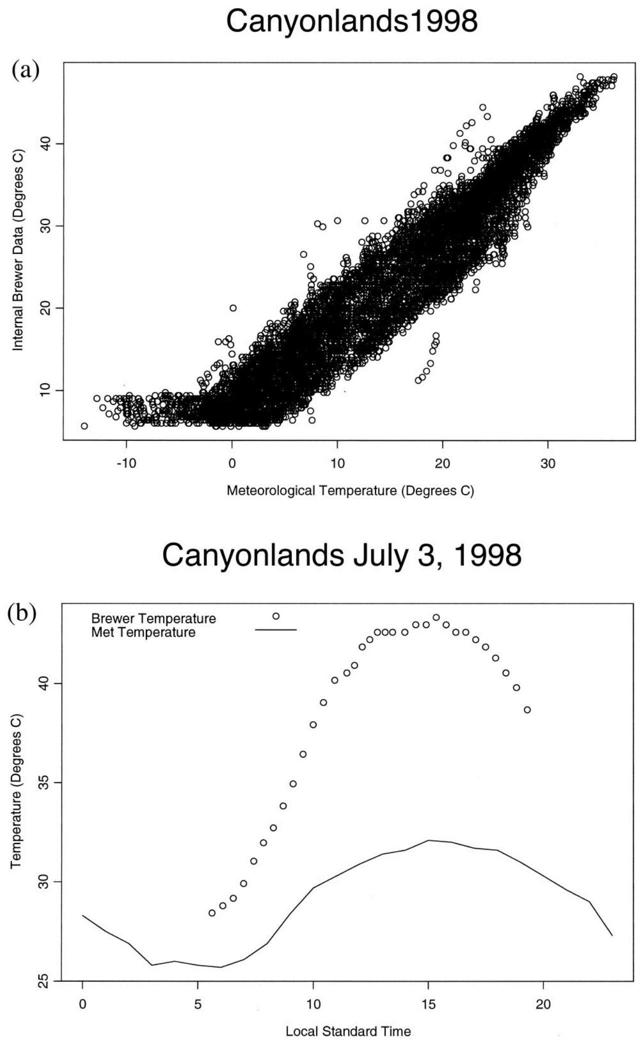

Figure 2. (a) Internal instrument temperature versus ambient temperature for Brewer 133 at Canyonlands National Park. (b) Diurnal cycle of internal and ambient temperatures. In general, the internal instrument temperatures are greater than the outside air values, and the magnitude of the difference between the internal and the ambient temperatures varies depending on time of day.

radiative heating than those at sea level. In most cases an instrument's internal temperature is considerably warmer than the ambient temperature. These differences are clearly illustrated in Figure 2b, which shows the diurnal cycle in ambient and internal temperatures for Brewer 133 at Canyonlands National Park. The differences are not necessarily linear or symmetric: the offset between the internal instrument temperature and the outside air temperature is often significantly greater in the afternoon than in the morning.

The Brewer instruments are equipped with heaters to help maintain the instrument's internal temperature at 9°C or above. The effect of an instrument heater can be clearly observed for Brewer 133 at Canyonlands (Figure 2a). Even with this warming of an instrument during colder time periods, there remains a large range over which internal temperatures vary. These internal temperature variations are known to change the absolute spectral responsivity of the instrument. The changes in responsivity in turn introduce biases into the spectral irradiance data. We illustrate in this paper that the biases are correctable as long as sufficient information about the instrument temperature dependence can be obtained, and that successful temperature corrections can reduce the errors in measurements by as much as 10%.

2.2. Temperature Characterizations

The external lamp tests conducted at the EPA/UGA and NPS sites provide enough information to attempt to characterize the temperature dependence for 20 of the Brewer instruments. As often as every 2 weeks, the operator at each of the sites places an external lamp on the UV dome/diffuser assembly of the Brewer instrument to check the instrument response. The raw data from these scans are recorded in XL files available via ftp from the University of Georgia. For a given site, a search of the XL files was made to find the dates when both the 50 W lamp scans and the 1000 W Brewer calibration were performed. The response of the instrument on these dates can be determined from the 1000 W NIST lamp calibration procedure [*Early et al.*, 1998]. The resulting calibrated spectral responsivity is combined with the 50 W lamp scan information to compute an irradiance for each 50 W lamp. This procedure ties the 50 W lamp scans to an absolute calibration and can be used to obtain an instrument-independent lamp irradiance. With this irradiance in hand, subsequent XL files using a particular 50 W lamp can be used to estimate the response of the instrument at the time of the scan. Because the 50 W lamp is unlikely to remain completely stable with time, the method is not perfect. Some errors may also be introduced if the temperature at the time that the 50 W lamp scan is performed is not the same as the temperature when the calibration is done.

We used this technique to calculate the Brewer response for all dates in which an XL file contained a scan from the chosen 50 W lamp. Because the XL file also contains the temperature for each scan, a time series was generated that included temperature and response. The time series was inspected visually to determine if any outliers existed in the data, or if any apparent step changes occurred in the response data as a function of time. For some sites, the response data showed a clear temporal linear decline with a superimposed annual cycle due to temperature effects. If no jumps were present in the data, the entire data set was used for the regression analysis. If obvious epochs existed within the data, attempts were made to do regression analysis on each epoch and to compare the results. In cases where multiple epochs were examined, the regression exhibiting the smallest uncertainty in the fitted parameters was used. Once a given epoch was selected for analysis, the mean response at each wavelength was removed from the time series to convert the response data into percent data. The derived coefficients could then be expressed in terms of percent per degree and percent per decimal year.

Instruments, as well as lamps, can degrade over time, introducing variability into the data set and confounding our ability to isolate temperature or other effects. We analyzed the Brewer data using a multiple least squares regression dependent on both time and temperature. The regression model used is a first-order least squares model with independent variables [e.g., *Neter et al.*, 1989] and has the form

$$R_{\lambda i} = \beta_{\lambda 0} + \beta_{\lambda 1}\mathrm{Temp}_i + \beta_{\lambda 2}\mathrm{Time}_i + \varepsilon_{\lambda i}. \tag{1}$$

For each observation i, $R_{\lambda i}$ is the relative instrument response at wavelength λ, Temp_i is the temperature associated with the

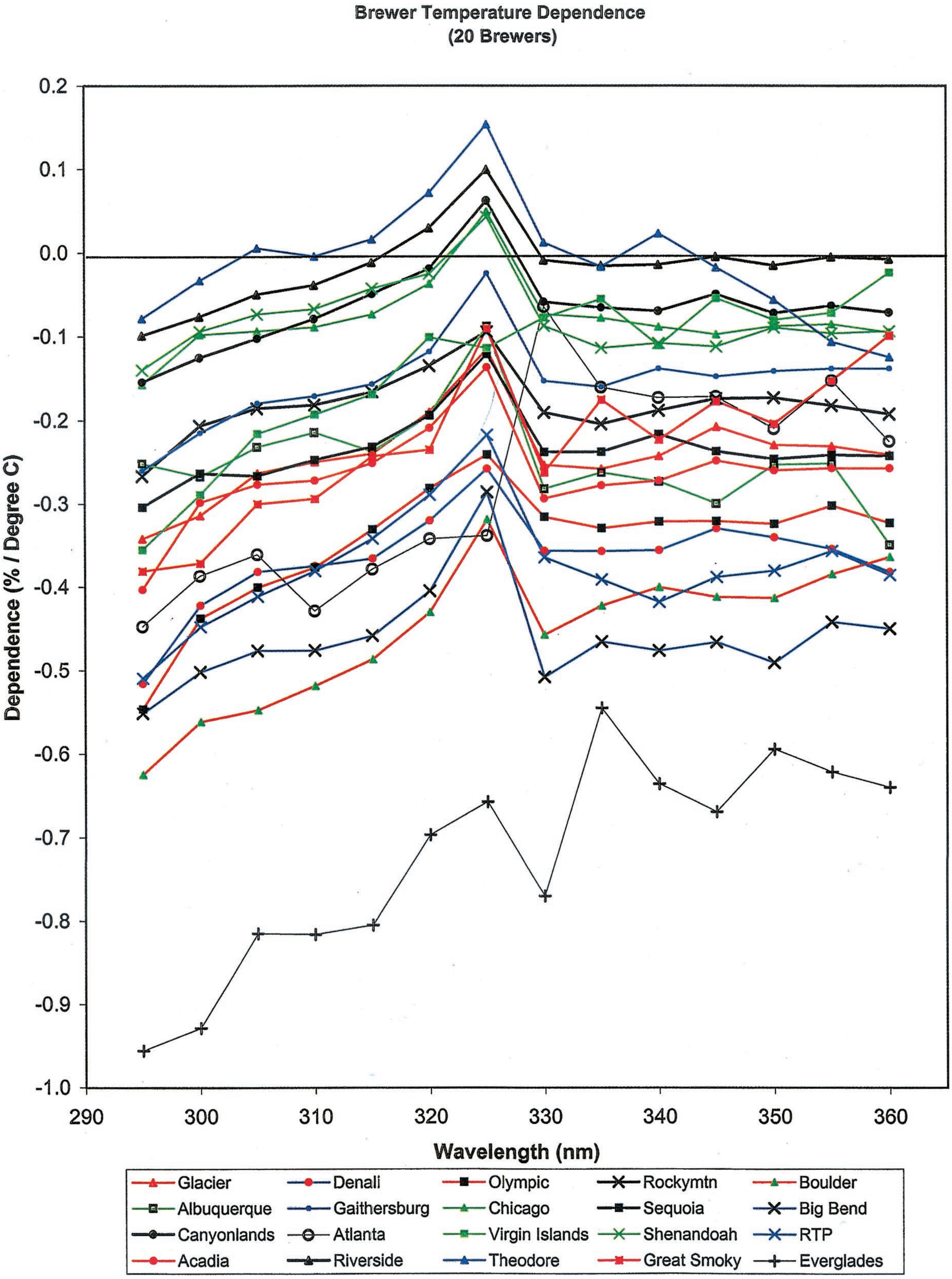

Plate 1. Change in response per °C as a function of wavelength for 20 Brewer instruments. Of the 20, ~18 seem to follow a consistent pattern, with the change in response being most pronounced at the shortest wavelengths and largely independent of wavelength above 325 nm. Brewer 140 (Hawaii) did not have enough data to characterize and is not included in this plot.

50 W lamp scan from the XL file, and Time_i is the time of the associated 50 W lamp scan (in decimal year), taken from the XL file. $\beta_{\lambda 0}$ is the model parameter that estimates the intercept value, $\beta_{\lambda 1}$ is the parameter that estimates the linear effect of temperature on response, and $\beta_{\lambda 2}$ is the parameter that estimates the linear effect of time on response; $\varepsilon_{\lambda i}$ represents the estimated error on $R_{\lambda i}$, where the errors are assumed to be normally distributed with a mean of zero. Using the multiple-regression approach, we can separate the changes due to each of the two independent variables, time and temperature.

Curves showing the percent change in response for a 1°C change in temperature were generated for each Brewer using the external lamp information. The time periods used for the characterizations (given in terms of Julian Day and year) are shown in Table 1. The table also lists the number of observations and the lamp numbers used to characterize the instrument temperature dependence at each site. The resulting characterizations, derived from the coefficients in equation (1), indicate the magnitude of temperature effect on the response at each wavelength.

For some sites, multiple scans were performed on a single day. These data are available in the XL files on the ftp site. For Brewer 103 (Chicago) there were enough 50 W lamp scans to derive a fit using a single day's data. A fit was also derived using data collected in the usual manner over a period of 11 months. The two resultant curves agreed quite well, especially over the UV-B region. The single-day characterization had much smaller statistical errors and is the fit shown in Plate 1. The good agreement for Brewer 103 implies that for at least some 50 W lamps the irradiance stays consistent enough with time to derive accurate temperature response curves from an intensive set of measurements. For Brewer 134 (Glacier), three 50 W lamps were used often enough to attempt a characterization for each. The curves were reasonably similar, and because the errors were not much different from one lamp to the next, the data from all three lamps were combined to calculate the final curve.

3. Results

For the majority of the instruments, the changes in the response are negative, indicating a decrease in the responsivity as temperatures increase. The derived 310-nm corrections for each instrument are shown in Table 1. At wavelengths less than 325 nm, the changes in response show a maximum positive value of 0.15% per °C. This value is approximately within the magnitude of the estimated temperature dependence of the lamp, so that adjusting for this effect gives a near-zero change in response. For Brewer 066, *Cappellani and Kochler* [1999] report the changes in the response to be negative with increasing temperature, similar to our results. The wavelength dependence of the change in response observed by Cappellani and Kochler for their single instrument is similar in both sign and general shape to our findings here. However, the magnitudes of the temperature response derived in our study span a larger range.

3.1. Wavelength Dependence

Results for 20 of the instruments are represented in Plate 1 as the change in response per 1°C as a function of wavelength. The results indicate a clear wavelength dependence of temperature effects below 325 nm. This finding is consistent with that reported by *Cappellani and Kochler* [1999], showing greater dependence at shorter wavelengths.

Above 325 nm the temperature dependence is relatively independent of wavelength. The magnitude of the disparity at 325 nm varies from instrument to instrument, and the values for the 20 instruments span a range that is statistically dissimilar.

The wavelength differences in the temperature dependence can be due to a number of sources. As a Brewer instrument performs a scan, a nickel sulfate filter is placed in the optical path for wavelengths below 325 nm. This nickel sulfate filter is known to be hygroscopic, and the specific effects of humidity or temperature on the filter require further study. The filter is housed between two UG11 filters that have been reported to degrade in the presence of UV radiation (Schott). For wavelengths above 325 nm where the nickel sulfate filter is absent, most instruments exhibit negative changes in the response that are independent of wavelength. Below 325 nm the filter appears to produce a wavelength-dependent contribution that could result from temperature-dependent changes in the width and position of its near-UV absorption band. Another probable source of temperature effects is the photomultiplier tube [*Singh and Wright*, 1987]. The electronic characteristics of the photomultiplier tubes may vary from instrument to instrument and may respond differently in a cool versus warm environment. The photomultiplier and nickel sulfate filter effects are thought to be independent and therefore additive and are expected to be the dominant contributors to the temperature dependence of the instruments.

3.2. Instrument Dependence

The range of internal temperatures and number of observations used to characterize the response for each of the Brewer instruments are shown in Table 1. The temperature corrections over the UV-B range were examined using a two-tailed student t-test with $n - 3$ degrees of freedom to determine whether the slopes of the temperature dependences at those wavelengths were statistically different than zero. The p values, indicating the probability that a slope would be detected as significant when, in fact, it is not, are also summarized in Table 1. For 15 of the instruments the results indicate that the change in response depends significantly on temperature in the region below 320 nm. The statistical significance is, however, influenced by the accuracy of the characterizations. For instruments with fewer observations the errors on the characterizations are larger, and the probability of accurately determining a statistically significant dependence becomes smaller.

Plate 1 shows the instrument-to-instrument similarities and differences with respect to temperature dependence. In the UV-B part of the spectrum the temperature dependences for the different instruments span a range from about 0.07% per °C to less than −0.95% per °C. Overall, the temperature response exhibits characteristic similarities among the 20 instruments. The standard errors of the temperature dependence between 295 nm and 360 nm were less than 0.1% per °C for 16 of the 20 Brewer instruments. These small error values indicate that many of the calculated temperature dependences do not overlap and that real instrument-to-instrument differences do exist. The range of values shown in the figure are not primarily due either to sampling effects or to random noise.

Table 1. Parameters Relating to UV Observations and Temperature Characterizations at Each of the Brewer Sites[a]

Site (Brewer Number)	Latitude/ Longitude	Elevation	Start Date	Internal Temperature Range (°C)(Used in Characterizations)	Number of Obs. Used	Time Period Used, Day and Year	50 W Lamp Used	310 nm Temperature Correction, %/°C	Range of CIE Correction	Ave p Value over UV-B Range
Glacier National Park, Montana (96–134)	48.7°N, 113.4°W	424 m	1997	3–38 (11–38)	42	20198–15300	451, 452, 453	−0.25	−6.65 to +1.81%	$P \ll 0.001$
Denali National Park, Alaska (96–141)	63.7°N, 149.0°W	661 m	1997	5–32 (13–31)	27	12798–23300	496	−0.37	−2.78 to +5.71%	$P \ll 0.001$
Olympic National Park, Washington (96–147)	48.1°N, 123.4°W	32 m	1997	8–35 (9–35)	48	20498–27800	522	−0.34	−1.58 to +5.38%	$P \ll 0.001$
Rocky Mountain National Park, Colorado (96–146)	40.0°N, 105.5°W	2896 m	1998	6–36 (11–35)	18	20100	512	−0.18	−3.16 to +2.33%	$P \ll 0.001$
Boulder, Colorado (93–101)	40.1°N, 105.2°W	1689 m	1996	−5–44 (12–43)	24	02699–03100	275	−0.52	−14.4 to +2.05%	$P \ll 0.001$
Gaithersburg, Maryland (105)	39.1°N, 77.2°W	43 m	1994	0–45 (0–45)	26	13794–03497	282	−0.17	−5.82 to +1.26%	$P < 0.001$
Acadia National Park, Maine (96–138)*	44.4°N, 68.3°W	137 m	1998	6–37 (7–35)	25	12197–20199	483	−0.27	−1.19 to +7.01%	$P < 0.001$
Everglades National Park, Florida (96–135)*	25.4°N, 80.7°W	18 m	1997	18–44 (26–44)	12	09299–24599	465	−0.82	−4.21 to +10.3%	$P < 0.001$
Chicago, Illinois (94–103)	41.8°N, 87.6°W	165 m	1999	−6–39 (11–35)	16	30299	279	−0.09	−3.44 to +0.75%	$P < 0.002$
Atlanta, Georgia (94–108)*	33.8°N, 84.4°W	91 m	1994	4–45 (23–45)	4	08999–23399	295	−0.43	−1.29 to +10.6%	$P < 0.002$
Research Triangle Park, North Carolina (92–087)	35.9°N, 78.9°W	104 m	1995	3–41 (10–36)	21	08598–13800	182	−0.38	−6.50 to +4.32%	$P < 0.025$
Great Smoky National Park, Tennessee (96–132)*	35.6°N, 83.8°W	564 m	1996	5–42 (12–41)	33	30398–35199	436	−0.29	−2.46 to +7.20%	$P < 0.025$
Big Bend National Park, Texas (96–130)	29.3°N, 103.2°W	329 m	1997	7–47 (26–44)	8	10020–27000	435	−0.48	−1.42 to +11.5%	$P < 0.02$
Albuquerque, New Mexico (94–109)*	35.1°N, 106.6°W	1615 m	1998	7–47 (20–47)	16	31999–25100	296	−0.21	−3.92 to +4.26%	$P < 0.05$
Sequoia National Park, California (96–139)*	36.5°N, 118.8°W	549 m	1998	7–46 (12–46)	17	29599–14300	488	−0.25	−2.34 to +5.99%	$P < 0.05$
Virgin Islands National Park, U.S. Virgin Islands (96–144)	18.3°N, 64.8°W	30 m	1998	28–45 (35–46)	25	08599–24900	506	−0.19	+0.04 to +2.22%	$P \sim 0.15$
Shenandoah National Park, Virginia (96–137)	38.5°N, 78.4°W	325 m	1997	7–37 (7–38)	53	34096–20000	476	−0.07	−0.81 to +2.15%	$P \sim 0.18$
Canyonlands National Park, Utah (96–133)	38.5°N, 109.8°W	814 m	1997	6–46 (13–41)	22	02798–22100	441	−0.08	−0.31 to +3.79%	$P \sim 0.18$
Riverside, California (94–112)	34.0°N, 117.3°W	84 m	1995	10–53 (16–50)	23	31294–28400	316	−0.04	no stat. sig. curve	$P \sim 0.75$
Theodore Roosevelt National Park, North Dakota (96–131)*	46.9°N, 103.4°W	238 m	1998	0–41 (11–35)	7	01999–27000	426	+0.01	no stat. sig. curve	$P \sim 0.80$

*A site that has a shift or other problem.

[a] Columns 2–4 give the latitude, longitude, elevation, and year observations were begun at each site; column 5 shows the internal temperature range (parentheses correspond to the range used for the characterizations); columns 6–8 show the number of observations, time period (Julian day and year), and 50 W lamp used; column 9 gives the 310 nm temperature correction derived using equation (1); column 10 reports the resulting range of CIE correction using the derived characterizations; and column 11 shows the average p value of slope of correction in the UV-B, indicating the probability that the correction would be falsely detected as significant. Of the 20 instruments characterized, 18 were found to exhibit a significant temperature dependence.

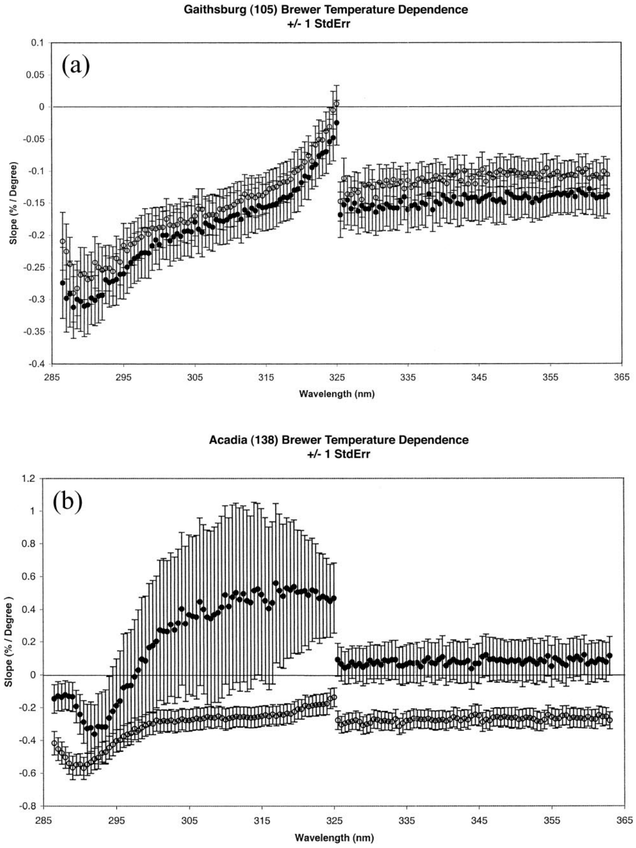

Figure 3. (a) Change in response per °C as a function of wavelength for Brewer 105 at Gaithersburg, Maryland. The curves represent the temperature dependence of the response from day 137, 1994, to day 34, 1997 (solid circles), and from day 112, 1997, to day 12, 1999, and show remarkable consistency between the two epochs, despite a switch-out of the $NiSO_4$ filter in 1997. The temperature range for the first epoch was 0° to 45°C; for the second epoch the range was 7° to 47°C. (b) Change in response per °C for two time epochs at Acadia National Park (Brewer 138). The open circles correspond to the time period from day 121, 1997, to day 201, 1999, over a temperature range of 7° to 35°C. The solid circles represent the time period from day 202, 1999, to day 263, 2000, having a temperature range of 7° to 32°C. The characterizations are statistically different at the alpha < 0.002 level for all wavelengths. The $NiSO_4$ filter is placed in the optical path for the shorter wavelengths and may explain the discontinuities observed at 325 nm.

3.3. Stability of the Temperature Dependence

The temperature dependences of the Brewer instruments were shown to be quite stable over our timeframe of observation. An example is instrument 105 at Gaithersburg, Maryland. Figure 3a illustrates that the temperature effects on the response of this instrument remained relatively consistent between 1994 and 1999. The characterizations for each time epoch clearly overlap within 1 standard error estimate.

Possible changes in the temperature dependence were observed for only two of the 20 Brewers evaluated in our study. Temperature corrections for two time epochs at Acadia National Park (Brewer 138) are shown in Figure 3b. These two time epochs are separated by a routine calibration of the instrument, and the records show no change-out of the photomultiplier tube or other potentially temperature-sensitive parts. We examine the statistical significance of the difference in the temperature dependence using a two-tailed t-test for independent samples with unrelated variances. For instrument 138, the temperature characterizations for the two epochs are statistically different at an alpha level of less than 0.002 over all wavelengths. Similar differences with time are observed for Sequoia National Park (Brewer 139). In this case, the instrument was serviced and the zenith prism was realigned between the two epochs. The temperature characterizations before and after the instrument adjustment were tested using the two-tailed t-test and were found to be statistically different at an alpha level of less than 0.001 for all wavelengths. Because the Brewer instruments involve a system of components operating in the field, it is difficult to isolate the exact causes of these changes. Nevertheless, the differences seen at Sequoia and Acadia suggest that averaging the change in response over all dates may not provide appropriate temperature corrections in all cases. Likewise, a characterization obtained using a single time period may not remain consistent over an entire observation record, unless the record itself remains largely stable.

Of the 20 Brewer instruments characterized in our analysis, the majority (18 of 20) did remain quite stable in terms of their temperature dependence over time. Error values on the derived temperature dependences were also quite small, indicating little noise in the temperature effects on the response over time.

3.4. Corrections to Irradiance Data

The curves obtained to characterize the temperature dependence provide estimates of the percent change in instrument response due to a temperature change of 1°C. For each observation the temperature at which the scan was taken can be compared against the temperature of the known response file, and the curve can be used to obtain a corrected response at each wavelength. Whether the resultant changes to the data are positive or negative depends on the temperature at which the instrument was calibrated. For the irradiance corrections, we adjust the temperature dependence of the response at each wavelength by an additional -0.05% to account for the 0.05 to 0.1% temperature dependence of the lamp output. By applying the temperature corrections to data for 18 of the Brewer sites we find that the changes in the retrieved daily CIE dose values fall within a range of -14 to $+12\%$. The resulting changes in the retrieved daily CIE dose are summarized in Table 1. The values given correspond to the 5 and 95% quantiles for the percent change in CIE dose.

Figure 4 shows the changes to the daily CIE dose at Boulder, Colorado, which are required to correct for the temperature dependence of the Brewer instrument. The errors introduced by the temperature effects are on the order of -15 to $+4\%$ and, most importantly, are not random. Because there is a clear seasonality in temperature, the effects on the spectral irradiance and dose observations are quantifiable. Were the temperature effects left uncorrected, the CIE dose values would be overestimated in the winter months and underestimated in the summer months. This suppression of the seasonal cycle could confound studies of the overall UV variation and its effects.

Similarly, the temperature dependence of the Brewer instruments can affect diurnal measurements of UV. Figure 5 shows the percent change in irradiance at four wavelengths after applying the corrections for the temperature effects. In the

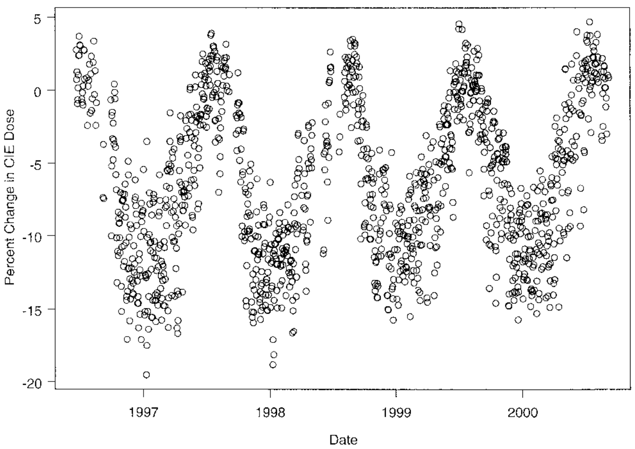

Figure 4. Percent change in daily CIE dose caused by temperature effects on Brewer 101 (Boulder, Colorado). The corrected values are higher than the measured values in the summer months, indicating that without the temperature corrections, UV would be underestimated in the summer when both temperatures and irradiance are highest.

earlier part of the day, when the instrument is cold, correcting for the temperature effects results in a decrease in the irradiance values. In the later part of the day, when the instrument has warmed, the temperature corrections slightly increase the irradiance values measured. The dotted line in Figure 5 represents the calculated UV index for the day in question. Were the temperature effects not corrected, the UV index values would be higher in the morning and slightly lower in the afternoon. These differences would introduce a false asymmetry into the measured diurnal cycle and could negatively impact various calculations, including use of the spectral UV data in Langley plots and for ozone estimation.

The temperature effects are a large contributor to the absolute uncertainty of the Brewer data. The effects are most pronounced at locations where the combined effect of the instrument sensitivity and the temperature variation, whether diurnal or seasonal, is largest. Correcting for these effects can improve the accuracy of the measurements on the order of 10% for sites experiencing daily temperature variations of 20°C or more. In addition, we have seen that changes to the calibration or to the components can directly affect the response of the instrument and must be accounted for in any robust characterization of the temperature dependence.

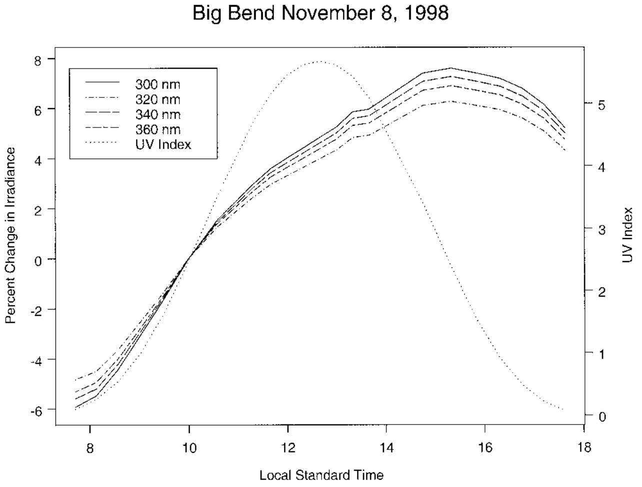

Figure 5. Percent change in irradiance due to temperature effects for Brewer 130 (Big Bend National Park). The values are given as a function of wavelength and time and indicate that without correction the measured irradiance would be overestimated in the early part of the day when temperatures are low and underestimated in the later part of the day when temperatures are higher.

4. Conclusion

Our methods make use of the existing external lamp data obtained for each Brewer instrument at varying time intervals to identify and remove the errors introduced by instrument temperature dependences. Temperature changes can affect the irradiance measured by the Brewer instruments by more than 5 to 10%. The temperature effects are generally greater at the shorter wavelengths and are roughly independent of wavelength above 325 nm. The effects vary among the instruments examined and depend on the range of temperatures observed at each site, as well as on the care and overall performance of each instrument. The external lamps used to measure the instrument response may themselves exhibit a temperature dependence, affecting the results by as much as 0.1% per °C. These issues must be carefully considered when developing appropriate temperature characterizations for the Brewer instruments. By characterizing the temperature dependence of the instruments and applying appropriate corrections to the data, we can reduce the effects and obtain results that are closer to the best accuracy attainable for these instruments.

Most of the Brewer instruments examined in our study appear to be well behaved with respect to temperature effects on the instrument response. However, some instruments may experience calibration and other changes that need to be taken into account. The instrument response, as well as temperature-induced changes to this response, can change over time as filters or other components are changed or replaced.

Understanding the effects of temperature on the instrument response is necessary to ensure consistent calibrations. Changes in temperature from one calibration to the next can affect the response and, if not accounted for, can introduce an artificial trend into the data. Likewise, for intercomparibility among the sites, we recommend that the data be corrected to a standard, uniform temperature. On the basis of work completed thus far, we suggest a standard temperature of 30°C.

Work is currently in progress by the National UV Monitoring Center (NUVMC) at the University of Georgia to improve temperature characterizations and apply the corrections to all of the data. New, temperature-corrected data will be archived at the NUVMC when the analysis is complete.

The 21 Brewer instruments operated by EPA/UGA and the National Park Service represent only a fraction of the Brewer instruments operated worldwide and represent only one type of Brewer (MarkIV). These instruments provide information on spectral UV levels over a range of elevations, terrain types, and ecosystems. The observations are useful to biological effects researchers and epidemiologists, as well as to atmospheric scientists. They also provide a means for improving satellite estimates of surface UV amounts, and for quantifying the effect of various surface and atmospheric features that need to be modeled for satellite retrievals. By better understanding and accounting for effects of temperature on the

Brewer instruments, we can improve the accuracy of the network data set. The temperature-corrected data provide improved information on seasonal changes in UV and on the magnitude of these changes from summer to winter. The improved data accuracy will also help to better characterize the diurnal cycle of UV radiation, an issue of particular relevance to the biological effects and epidemiological communities.

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