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Trends and interannual variability in surface UVB radiation over 8 to 11 years observed across the United States

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[1] The United States Department of Agriculture UVB Monitoring and Research Program maintains a network of Yankee Environmental Systems surface UVB-1 meters distributed throughout the United States. We analyzed behavior of surface UVB radiation (280–320 nm) over 8 to 10 years measured at eight stations within this network that were selected because of their early deployment (ranging from 1995 to 1997). These eight stations represent different climates, latitudes, and land cover types. We characterized differences in instrument sensitivity and drift through a methodology that utilized regular laboratory calibrations of field instruments and calibration of standard meters to spectroradiometers. From 3-minute observations, we computed mean annual and mean monthly irradiances at each site to study trends and interannual variability in UVB irradiance. Annual irradiance changes ranged from −5% per decade to +2% per decade across the sites. Confidence intervals were computed with a statistical model that included autocorrelation and measurement uncertainty. Resulting 95% confidence intervals were large and included 0, partly as a result of the short time series. We calculated trends at each site for individual months (for January, February, etc.), which are important for assessing effects on human health, crops, and other organisms whose sensitivity to UVB exposure changes seasonally. Positive and negative monthly trends of different magnitudes were measured, although trends in most months at most sites were not statistically significant from 0. The largest absolute changes were generally in spring, summer, and fall, and large relative trends occurred in winter in most locations compared with other seasons. Interannual variability of surface UVB radiation was 2% to 5% of the mean. Our study illustrates that, using a well-calibrated instrument record, the 10 years beginning around 1995 did not show significant trends in surface UVB irradiance at stations across the United States. Our observed range of trends occurred during a period of generally increasing midlatitude column ozone, suggesting that changing cloud, aerosol, and snow conditions were responsible for driving surface radiation variability in addition to ozone trends.

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1. Introduction

[2] Ultraviolet (UV) radiation affects the health of plants and animals (including humans) through absorption by tissues, subsequent damage, and possible repair [*Caldwell et al.*, 2003]. Surface UV radiation is primarily affected by solar zenith angle (SZA, the angle between the Sun and zenith; a function of latitude, time of year, and time of day) and atmospheric conditions, most notably clouds, ozone, and aerosols [*Madronich*, 1993]. Changing atmospheric conditions associated with several processes have led to concern about whether UVB radiation (defined as between 280 and 320 nm) is changing. First, with the buildup of atmospheric chlorine in the past several decades, severe stratospheric ozone depletion has been documented over the winter poles since 1980 and reduced but still important decreases have been observed at middle latitudes [*WMO*, 2003]. The concentration of plant, animal, and human life outside of the high latitudes implies that even relatively minor changes in stratospheric ozone could have important impacts on surface UV radiation and thereby on biological health [*Caldwell et al.*, 2003].

[3] Climate change is a second factor that may be influencing surface UV radiation. An accelerated hydrologic cycle has been documented in several regions [*Easterling et al.*, 2000], and projections of future climate include contin-

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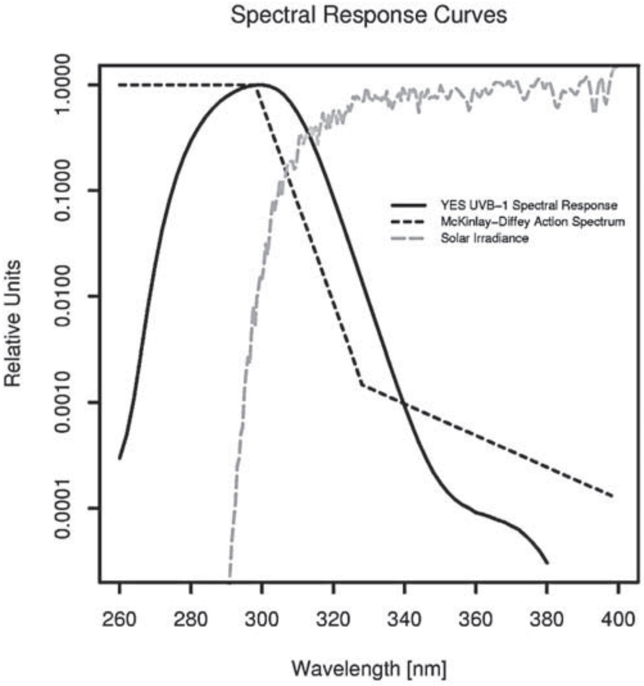

Figure 1. YES UVB-1 spectral response used for instrument calibration factors (solid black curve), CIE erythema action spectrum (dashed black curve) [*McKinlay and Diffey*, 1987], and solar irradiance (long-dashed gray curve).

ued changes [*IPCC*, 2001]. Associated alterations in cloud properties, including cover and optical thickness, will affect the attenuation of UV radiation and therefore amounts incident on the surface. Snow cover influences measured surface UV radiation through enhanced scattering [*Fioletov et al.*, 2001]; thus any effects of warming temperature or changing precipitation that modifies snow cover will also alter surface UV radiation.

[4] Finally, changing aerosol properties from pollution and land-use dynamics affect the surface UV budget. With the increase in fossil fuel burning beginning in the early nineteenth century, aerosol loadings have risen dramatically. In addition, overgrazing and agricultural intensification may have resulted in land degradation that acts as a source of dust to the atmosphere [e.g., *Tegen and Fung*, 1995], though estimates are subject to large uncertainties [*Mahowald and Luo*, 2003].

[5] Both ground- and space-based instruments are used to measure surface UV irradiance. Ground-based instruments have the advantage of directly observing the downwelling radiation, but lack the spatial coverage of satellite retrievals. Long-term studies of measured UVB radiation have been conducted at numerous sites [*Borkowski*, 2000; *Fioletov et al.*, 2001; *Gantner et al.*, 2000; *Kaurola et al.*, 2000; *McKenzie et al.*, 1999; *Roeder*, 2002], often taking advantage of additional collocated radiation measurements to reconstruct UV radiation data sets and extend them further back in time.

[6] Few studies of spatially extensive ground-based UV radiation data exist due to the paucity of networks and difficulty of analysis of such measurements. As an example, an early analysis of one network in the United States reported no increases or slight decreases from 1974 to 1985 [*Scotto et al.*, 1988], though later analysis that accounted for changes in calibration methods found increasing radiation with the same data set [*Weatherhead et al.*, 1997].

[7] Here we describe surface UVB radiation measured by a network of ground-based instruments run by the United States Department of Agriculture (USDA) UV Monitoring and Research Program at Colorado State University [*Bigelow et al.*, 1998]. Eight sites with operating time periods of 8–11 years were selected for trend analysis. These sites are distributed across the conterminous United States, thus allowing an investigation of UV radiation changes across a continent. Means, interannual variability, and trends of monthly and annual mean irradiance were calculated to explore behavior across sites and to assess the seasonal timing of changes.

2. Methods

2.1. Instrumentation

[8] We analyzed measurements from the USDA UVB network of UVB-1 meters manufactured by Yankee Environmental Systems (YES). The UVB-1 meter is a broadband pyranometer designed to replicate the erythemal action spectrum, though the instrument's spectral response deviates from the erythema response and extends from approximately 290–380 (Figure 1). The UVB-1 measures global downwelling irradiance primarily in the UVB (280–320 nm) spectral region by using a combination of colored glass filters. (Throughout this paper, the measured quantity is referred to as UVB irradiance, although more accurately this quantity is an instrument-weighted solar irradiance.) A UV-sensitive fluorescent phosphor converts the UVB radiation to visible light, which is then measured with a solid-state photodiode. The YES UVB-1 radiometer is heated to 45°C with an internal heater to minimize the temperature dependence of the spectral response.

[9] The USDA UVB network has operated UVB instrumentation since 1994. For this study, we chose the eight sites with the longest UVB records. Site locations and information are listed in Table 1. For the eight chosen sites, complete years began in 1995 except for NM01 and ME11 (1996) and MD01 (1998). We chose to analyze only complete years; hence, observations associated with incomplete records in beginning deployment years were discarded.

2.2. Calibration

[10] We analyzed the instrument-weighted solar irradiance instead of converting to, for example, erythemally weighted irradiance. This analysis simplified the calibration procedure as we did not need to account for the difference between the erythemal response and instrumental response that would require corrections based on solar zenith angle and total ozone as described below [*Lantz et al.*, 1999].

[11] The formula employed to convert voltages to instrument-weighted irradiance is

$$F = V \times ICF(\theta) \times SF(\theta), \tag{1}$$

Table 1. Site Descriptions

Code	Name	Latitude/Longitude	Elevation (m)	Land Cover Type	First Complete Year	Length of Record (years)
CA01	UC Davis Climate Station, Davis, CA	38.53°N, 121.76°W	18	agriculture	1995	11
CO01	Central Plains Experimental Station, Nunn, CO	40.79°N, 104.75°W	1641	shortgrass steppe	1995	11
GA01	Bledsoe Research Station, Griffin, GA	33.18°N, 84.41°W	270	agriculture	1995	11
IL01	Bondville Road Station, Bondville, IL	40.04°N, 88.36°W	213	agriculture	1995	11
MD01	Wye Research and Education Center, Queenstown, MD	38.91°N, 76.14°W	7	agriculture	1998	8
ME11	Northern Maine Regional Office, Presque Isle, ME	46.68°N, 68.03°W	144	urban/suburban	1996	10
NM01	Jornada Experimental Range, Las Cruces, NM	32.61°N, 106.74°W	1317	desert	1996	10
WA01	Albion Field Station, Pullman, WA	46.75°N, 117.18°W	804	agriculture	1995	11

where F is the instrument-weighted irradiance in W m^{-2}, V is voltage, SF (unitless) is a scale factor that adjusts each instrument to the reference radiometer(s), and ICF ((W m^{-2})/V) is the instrument calibration factor that converts voltages from the reference radiometer to the instrument-weighted irradiance. θ indicates that SF and ICF are dependent on solar zenith angle.

[12] *ICF* is calculated from a calibration constant (C_i), a spectral response correction factor (f_i) that depends on solar zenith angle (θ) and total column ozone (Ω), and an angular response correction factor (f_c) that depends on θ:

$$ICF(\theta, \Omega) = C_i^{*} fi(\theta, \Omega)^{*} fc(\theta). \tag{2}$$

C_i is determined by comparing simultaneous measurements of instrument-weighted solar irradiance measurements from a spectroradiometer to the measured voltage (V) of the radiometer in the field with the sun as a source for a given solar zenith angle and total ozone. The weighting function applied to the spectroradiometer measurements is the spectral response function representing the suite of over 45 radiometers used in the USDA Network (Figure 1). f_i corrects for the spectral mismatch between the spectral response of the individual broadband radiometer and the instrumental spectral response of the reference triad. f_c accounts for the nonideal angular response of the radiometer and is a function of the cosine measurement of the instrument in the laboratory in several planes and the local sky conditions.

[13] The YES UVB-1 radiometers have been calibrated and characterized for spectral response and cosine response approximately once per 1–2 years for the last 8–11 years. The spectral responses among these radiometers are remarkably similar and have changed little from year to year [*Lantz et al.*, 2006]. Therefore we ignored f_i in equation (2), removing the need to include total ozone to calculate F. Any differences of spectral response and angular response among radiometers would be evident in the solar zenith angle dependence of SF. Across radiometers, this dependence averages 0–3% for SZAs from 20° to 85°. The majority of this SZA dependence is from 20% of the radiometers that were built in 1993, with the remaining 80% ranging from 0.0% to 0.4% [*Lantz et al.*, 2006]).

[14] The stable spectral and angular characteristics across instruments and through time make this instrument excellent for monitoring activities because instruments can be swapped out in the field and returned for calibration without significant loss of information or significantly increased uncertainties. Within the USDA UVB network, instruments were rotated in and out of each site following the established network protocol to maintain continuous measurements while the instruments are sent away for calibration.

[15] Two calibration methodologies existed during the study period (1995–2004), and an accurate and consistent calibration procedure was required to assess changes in UVB over this period. For the first few years, until 1998, instruments were calibrated and maintained by YES. Each instrument was sent to YES, nominally annually, where it was compared against a YES reference UVB-1 meter. The instrument under test was physically adjusted so that its output voltages matched the reference's voltages (to a manufacturer's specification of 5%). This is equivalent to the SF determination by the CUCF described below.

[16] The YES reference radiometer itself was calibrated in 1993 and 1999 using a collocated spectroradiometer with the sun as the source. Calibration constants that converted the reference UVB-1 voltages to integrate instrument irradiance (1/*ICF*) were 1.97 V/(W m^{-2}) in 1993 and 2.03 V/(W m^{-2}) in 1999. *Frederick et al.* [2000] describe the spectroradiometer calibration methodology in greater detail. The apparent 3% increase in YES reference radiometer sensitivity was within the uncertainty of typical spectroradiometer calibrations [*Bernhard and Seckmeyer*, 1999] and therefore may not represent a true increase.

[17] In late 1997 (varies by instrument), calibration responsibilities were moved from YES to the Central UV Calibration Facility (CUCF) run by NOAA in Boulder, Colorado. CUCF maintains a triad of YES UVB-1 meters used as reference radiometers [*Lantz et al.*, 1999]. Instruments in the field were transported to CUCF annually and compared to the CUCF reference triad for a 2-week period to determine each radiometer's scale factor (*SF*). *SF* forces each instrument to match the output of the CUCF triad. Its application is equivalent to the physical adjustment performed by YES in prior years.

[18] A challenge of analyzing time series of these UVB-1 irradiances was the integration of the two calibration methodologies. To accomplish this, we first applied the CUCF *SF* to each instrument, interpolating between calibration dates when available, using the earliest or latest calibration date otherwise. Pre-1998, when YES physically adjusted each instrument to match the YES reference radiometer, we applied the earliest *SF* calculated by CUCF.

[19] Calibration drifts in the reference radiometers (i.e., changes to ICF) were analyzed with the two YES calibrations in 1993 and 1997 [*Frederick et al.*, 2000] and using the CUCF ICF calibrations that occurred from 1998 forward. Figure 2 plots ICF values derived from spectroradi-

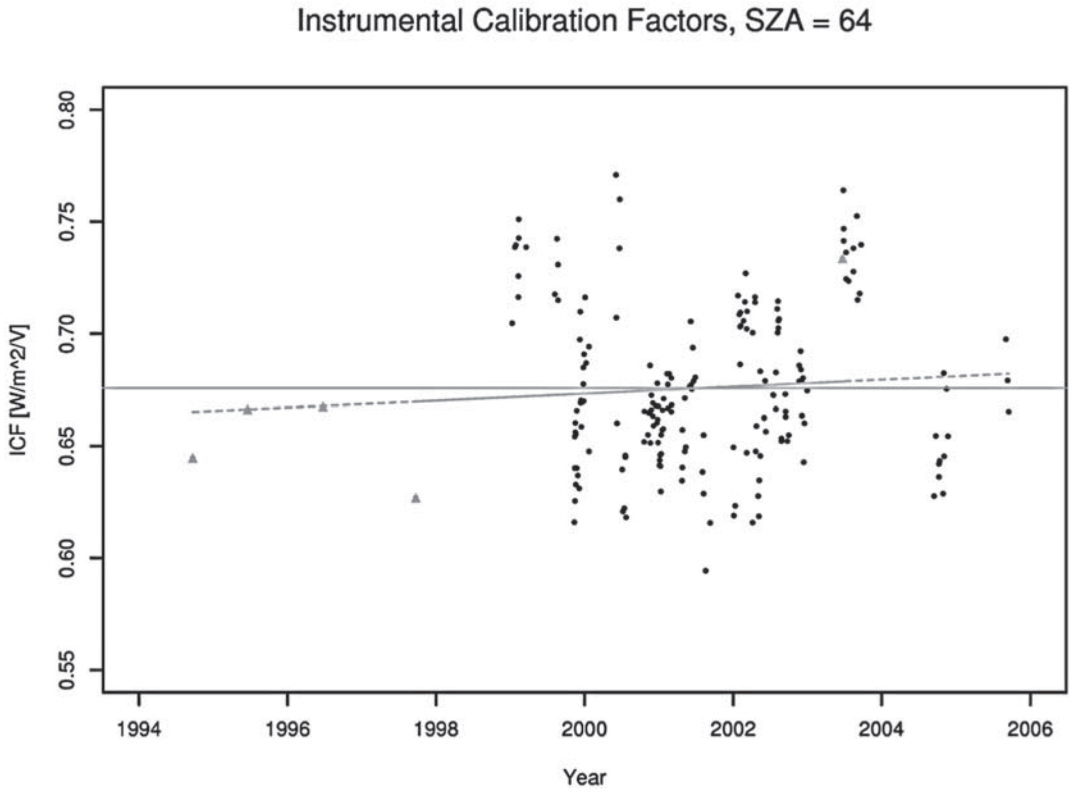

Figure 2. Time series of ICF, the instrument calibration factor that converts voltages from a standard instrument to the integrated instrument irradiance. The shaded triangles indicate an ICF calculation during a North American intercomparison campaign [*Early et al.*, 1998a, 1998b; *Lantz et al.*, 2002]. The lack of significant trend in ICF indicates the stability of the standard instruments used by the NOAA Central UV Calibration Facility.

ometer measurements during North American spectroradiometer intercomparisons from 1997 to 2005 at a solar zenith angle of 64°, chosen to maximize the number of calibration days across the year [*Early et al.*, 1998a, 1998b; *Lantz et al.*, 2002]. A linear regression of ICF values over the time period reveals a slope of 0.0004 (W m^{-2})/V/year. The change in ICF during this period is insignificant compared with the mean value during this period (0.67 ± 0.08 (W m^{-2})/V). Because both the YES calibrations and the CUCF calibrations revealed no change in ICF within the uncertainty of the measurements, we set ICF to the solar zenith angle-dependent ICF values in 1997 and specified no temporal trend.

[20] Uncertainties in calibration include those associated with the UVB-1 radiometers, as well as the calibrating spectroradiometers. The total uncertainty in the calibration of a radiometer includes the uncertainty in the adjustment of the output of the radiometer (pre-1998) or the determination of the scale factor (*SF*) (post-1998) plus the uncertainty in the calibration of the reference radiometers against the precision spectroradiometer. The manufacturer quotes the uncertainty in the adjustment (equivalent to the CUCF's *SF*) as ±5% [*Frederick et al.*, 2000]. The average standard deviation (2σ) of *SF* for the suite of radiometers is ±0.6% for the 2-week period calibration period at the Table Mountain test site. *SF* changes across the year can be estimated based on a few representative radiometers that have been at the Table Mountain test site for at least a year. The temporal standard deviation in *SF* for radiometers with typical spectral and angular response characteristics is ±0.6% (2σ). A subset of radiometers built in 1993 have a different angular response (20% of suite of radiometers); a radiometer of this type has an *SF* standard deviation of 3.3% across the year (2σ). A study of the stability of the radiometers' scale factors from 1997 to 2005 gave an average change per year of 0.05%/year for the suite of radiometers that excluded repaired radiometers, with a maximum change <5% over the 1997–2005 period [*Lantz et al.*, 2006]. This value is less than the manufacturer's specification of 5%, and therefore we used the higher value.

[21] The uncertainty of ICF is reflected in the variability around the mean. This high variability could be due to several factors either in the spectroradiometer or radiometer measurements used to calculate ICF. The estimated uncertainty of the spectroradiometer measurements is ±5%, which includes temperature dependence of optical components, angular response correction uncertainties, and diffuser contamination [*Bernhard and Seckmeyer*, 1999]. Another factor is the dependence of the radiometer signal on humidity and temperature [*Huber et al.*, 2002, 2003]. *Huber et al.* [2002, 2003] results were based on a radiometer of a similar design but a different manufacturer. Because the YES UVB-1 is maintained at a higher temperature, these effects are likely smaller than for the type of radiometer in their studies. The uncertainty in the angular response correction can be quite large and is a significant cause of

the total uncertainty. This occurs because the angular response of these radiometers deviates significantly from the ideal response, where the angular response correction assuming an isotropic sky is approximately 10% at solar zenith angle of 20° and 22% at a solar zenith angle of 80°. An accurate correction requires knowledge of the partitioning into direct and total solar components and knowledge of the sky radiance distribution. These factors depend on the atmospheric conditions such as the presence of clouds and aerosols.

[22] Adding the uncertainty of the ICF determination (±12%) to the maximum scale factor (*SF*) uncertainty of 5% in quadrature results in a total uncertainty $2\sigma_m$ of ±13% for each monthly or annual observation.

2.3. Analysis

[23] To calculate annual mean UVB irradiances, we averaged all valid 3-minute measurements within the year. We tested whether this resulted in biases in the annual UVB (due to loss of measurements during only noon hours, for example) by comparing the sum of the cosine of the solar zenith angle for valid measurements with the sum for all daylight hours. In only a few cases was the sum of valid measurements less than 90% of the total (GA01: 1995 (89%), 2002 (85%), 2003 (89%); IL01: 1998 (86%)). Furthermore, inspection of months of missing data revealed no bias in the seasonal timing across years (within one site).

[24] We averaged irradiance during each month for each site. We used these monthly irradiances to produce time series for each month that had lengths corresponding to the number of observing years at each site (8–11 years), for example, the 11 Januarys (1995–2005) that occurred at GA01. This analysis method ensured comparison among times with similar clear-sky irradiances based on the noon-time solar zenith angle. That is, a time series of all monthly irradiances (January through December of each year) hides variability in the Januarys due to lower clear-sky irradiance during those months. We wanted to capture the seasonal timing of changes in UVB radiation, which may determine whether organisms might respond to such changes [*Barnes et al.*, 1995]. Similar to the annual values, we calculated the fraction of valid measurements weighted by the solar zenith angle and applied a threshold of at least 80% valid measurements. This resulted in some missing months at some sites, for example, during each July 2000–2004 at GA01. Sensitivity tests using thresholds of 70 and 90% instead of 80% revealed very little change in the mean annual cycle of monthly irradiances. Furthermore, only 3 months across all sites had significant changes in the monthly trends that resulted from modifications to the number of years included in the trend calculation (July at GA01, August at MD01, and July at ME11).

[25] We chose to calculate confidence intervals around the trends instead of significance levels because confidence intervals provide additional information beyond whether a trend was different from zero. When confidence intervals do not include zero, similar conclusions can be drawn as when trends significantly differ from zero. To calculate confidence intervals for trends in the time series, we first define a model that describes measurement uncertainty with possible contamination by autocorrelation. We initially performed a linear regression study of the observed monthly or annual UVB irradiance y_i on the year x_i. An inspection of the Durbin-Watson test statistic [*Durbin and Watson*, 1950] indicated the presence of autocorrelation or indeterminate autocorrelation in the vast majority of the residual series. To account for possible autocorrelation, we used the first-order autoregressive model

$$\mathrm{z_i} = \rho \mathrm{z_{i-1}} + \varepsilon_{\mathrm{i}}, \tag{3}$$

where $-1 \leq \rho \leq 1$ measures autocorrelation and $\{\varepsilon_i\}$ are independent and identically distributed normal random variables with mean 0 and variance σ_ε^2 (written iid $N(0, \sigma_\varepsilon^2)$). We also assumed

$$y_i = (\beta_0 + \beta_1 x_i + z_i)(1 + \alpha_i), \tag{4}$$

where β_0 is the unknown intercept, β_1 is the unknown slope of the linear trend, and $\{\alpha_i\}$ are iid $N(0, \sigma_{\mathrm{m}}^2)$ measurement errors (with σ_{m}^2 known) that are independent of $\{\varepsilon_i\}$. The process $\{z_i\}$ represents the autocorrelated errors in measuring UVB irradiance. Note that z_i has variance $\sigma_\varepsilon^2/(1 - \rho^2)$ because $\{z_i\}$ is a first-order autoregressive process [*Brockwell and Davis*, 1991]. This model is linear and therefore will not capture nonlinear behavior; however, inspection of the annual irradiance time series suggests this is a reasonable assumption.

[26] The unknown parameters β_0, β_1, σ_ε^2, ρ were estimated from the observations as follows. Let $\hat{\beta}_0$, $\hat{\beta}_1$ be the estimates of the slope and intercept, respectively, and $\{r_i\}$ be the residuals from the least squares regression of y_i on x_i. We define $g_0 = \sum_{i=1}^{n} r_i^2/n$, $g_1 = \sum_{i=2}^{n} \{r_i r_{i-1}/n$ and $v = \sigma_{\mathrm{m}}^2 \sum_{i=1}^{n} (\hat{\beta}_0 + \hat{\beta}_1 x_i)^2/n$. If $g_0 \leq v$, then the residual variability was dominated by measurement uncertainty, and we set $\tilde{\rho} = 0$, $\tilde{\sigma}_\varepsilon^2 = 0$. Otherwise, we set $\tilde{\rho} = g_1 (1 + \sigma_{\mathrm{m}}^2)/(g_0 - v)$, estimated ρ by $\hat{\rho} = \max\{-1, \min\{\tilde{\rho}, 1\}\}$, and estimated σ_ε^2 by $\hat{\sigma}_\varepsilon^2 = (g_0 - v)(1 - \hat{\rho}^2)/(1 + \sigma_{\mathrm{m}}^2)$. These estimates are referred to as method of moments estimates because they are obtained by replacing variance and covariance expressions for the residuals $\{r_i\}$ with the sample moments g_0 and g_1, respectively [*Lindgren*, 1993].

[27] We obtained a confidence interval for the trend slope β_1 using a parametric bootstrap technique. For each of b = 1, 2, …, 10,000, we generated a synthetic time series using the estimates $\hat{\beta}_0$, $\hat{\beta}_1$, $\hat{\sigma}_\varepsilon^2$, and $\hat{\rho}$ as follows:

[28] 1. First, generate $z_0^{(\mathrm{b})}$ and $\{\varepsilon_i^{(\mathrm{b})}\}$. If $\hat{\rho} = \pm 1$, then $\hat{\sigma}_\varepsilon^2 = 0$ and set $z_0^{(\mathrm{b})} = r_1/\hat{\rho}$ where r_1 is the first residual in the linear regression done above and $\varepsilon_i^{(\mathrm{b})} = 0$ for i = 1, 2, …, n. Otherwise, if $\hat{\rho} \neq \pm 1$, then we simulate $z_0^{(\mathrm{b})}$ from $N(0, \hat{\sigma}_\varepsilon^2/(1 - \hat{\rho}^2))$, and independently simulate $\{\varepsilon_i^{(\mathrm{b})}\}$ as iid $N(0, \hat{\sigma}_\varepsilon^2)$ for i = 1, 2, …, n, and assign zeros if $\hat{\sigma}_\varepsilon^2 = 0$.

[29] 2. Independently simulate $\{\alpha_i^{(\mathrm{b})}\}$ as iid $N(0, \sigma_{\mathrm{m}}^2)$ measurement errors for i = 1, 2, …, n.

[30] 3. For i = 1, 2, …, n, form

$$\begin{aligned} z_i^{(b)} &= \hat{\rho} z_{i-1}^{(b)} + \varepsilon_i^{(b)} \\ y_i^{(b)} &= \left(\hat{\beta}_0 + \hat{\beta}_1 x_i + z_i^{(b)}\right)\left(1 + \alpha_i^{(b)}\right). \end{aligned} \tag{5}$$

[31] 4. Obtain the estimates $\hat{\beta}_0^{(\mathrm{b})}$ and $\hat{\beta}_1^{(\mathrm{b})}$ of the unknown trend parameters for the bth synthetic times series by linear regression of the simulated irradiances $y_i^{(b)}$ on the year x_i.

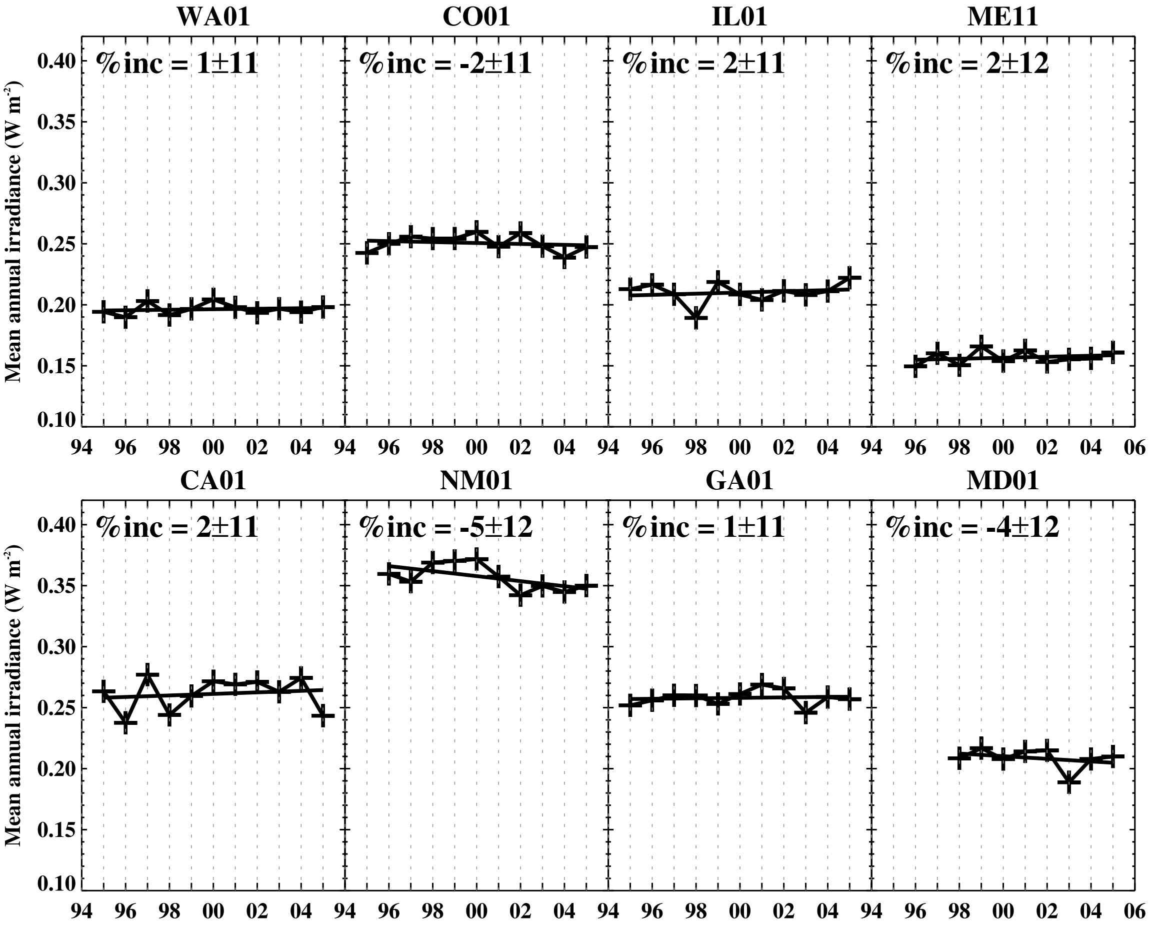

Figure 3. Mean annual irradiance (W m^{-2}) at each site. Percent increases over the site measurement period and 95% confidence intervals. Plots are organized roughly by geographic location.

[32] The 250th and 9750th smallest values among the 10,000 $\hat{\beta}_1^{(b)}$ values provide a 95% bootstrap confidence interval for β_1. The 95% confidence intervals calculated using the above formulations are plotted in the trend figures.

3. Results

3.1. Annual Irradiance

[33] Annual time series of UVB irradiances at all sites show the influences of latitude and therefore solar zenith angle (Figure 3). More southern sites (GA01 and NM01) recorded more irradiance than the more northern sites (WA01, ME11). Climate influences, in particular cloudiness, also affected the measured radiation. Mean values at CA01 and CO01 were similar, whereas a site at a similar latitude (MD01) had smaller annual values. Of the three sites, more cloudy days occurred per year at MD01 (164) than at the other sites (100 at CA01, 120 at CO01; from Northeast Regional Climate Center, http://met-www.cit.cornell.edu/ccd.html). Furthermore, the timing of clear skies with respect to solar zenith angle affected the mean irradiance. In California, summertime is consistently clear, with 22 clear days per month (~73%), whereas during the same period about 33% of the days are clear in Colorado and about 25% are clear in Maryland. Elevation also influences mean irradiance. The two higher elevation sites, CO01 and NM01, measured higher values partly as a result of cleaner air and reduced molecular scattering.

[34] Stations experienced increases or decreases in annual UVB irradiance over the 8- to 11-year period (Figure 3). To account for variability in the length of site records and standardize the increases, these percent increases were normalized to 10 years (Figure 4) by dividing by the number of years of observations at each site, then multiplying by 10. Percent changes varied from a low of −5% per decade at NM01 to a high of 2% per decade (CA01, IL01, ME11). Five of the eight sites had increases, whereas three had decreases. Large confidence intervals that included 0 resulted in large part from the short time series. Geographically, no spatial patterns were apparent in the trends.

[35] Interannual variability at the different sites was analyzed with the temporal standard deviation and coefficient of variation (CV; standard deviation divided by the mean; Figure 5). CA01 and NM01 had the largest absolute interannual variability, and ME01 and WA01 had the smallest absolute variability. The interannual variability was about 2−5% of the mean irradiance. The CV at CA01 was highest of the sites. The CV at NM01 was reduced compared to the standard deviation as a result of the large annual irradiances measured there. IL01, MD01, and ME11 had the larger CV values, and the smallest CV occurred at WA01.

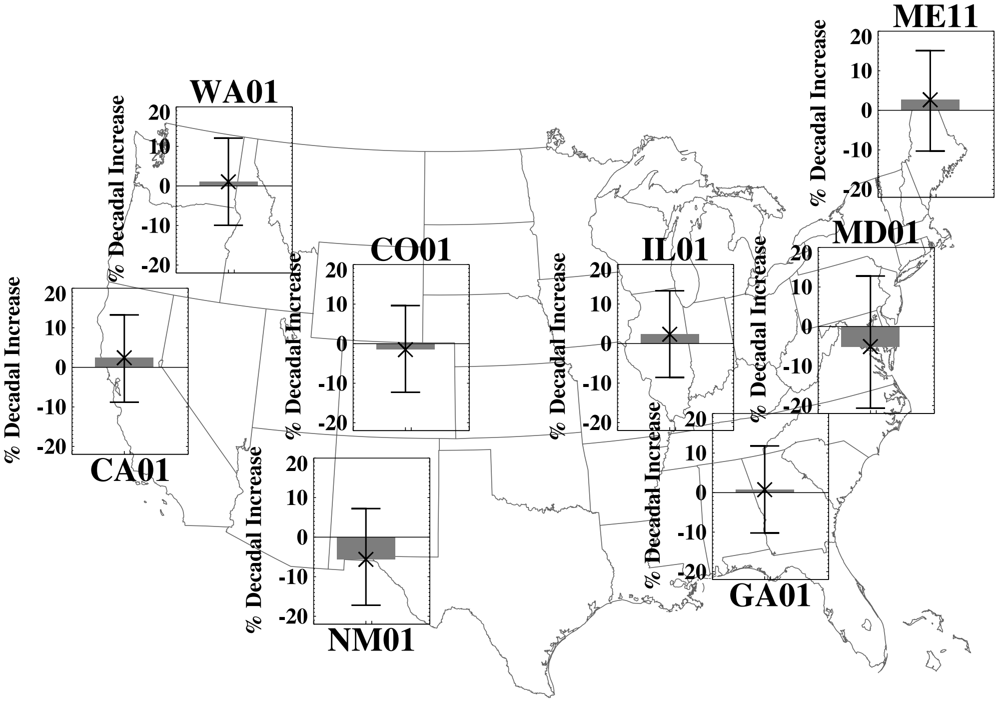

Figure 4. Percentage increase in annual irradiance at each site normalized to 10 years to account for variability in the length of station records; 95% confidence intervals were also plotted.

3.2. Monthly Irradiance

[36] Annual cycles of mean monthly irradiance were similar at all sites, with peaks occurring in July at most sites (Figure 6). New Mexico is an exception: elevated cloudiness associated with the summer monsoon reduced irradiance in July compared with June. The three easternmost sites (ME1, GA01, MD01) were slightly different from the rest in that the summertime maximum occurred over several months. At GA01, for example, high monthly irradiance occurred from May through August.

[37] Absolute increases were frequently largest from April through September across sites, consistent with the highest monthly irradiances (Figure 6, lower curves in each panel). However, at NM01, the maximum absolute change (a decrease) occurred in February, and at ME11, the maximum change (an increase) occurred in September.

[38] All sites had at least one month when the relative decadal change exceeded 10% (Figure 7). As with the annual irradiance, monthly increases had wide confidence intervals that included 0. Within a site, the largest change often occurred in winter months when the absolute irradiance was lowest. However, CO01, IL01, ME11, and MD01 had large relative trends in other seasons.

[39] Interannual variability (CV) in monthly irradiance at each site was typically highest in spring and lowest in winter, with large ranges in the magnitude of CV during the year at each site (Figure 8). CO01, CA01, GA01, and MD01 had spring CV values >0.03. December and January CV were generally <0.01, with ME11 exhibiting the lowest winter CV.

4. Discussion

[40] Our results add to a body of knowledge of trends of UVB radiation. *Scotto et al.* [1988] found unchanging or decreasing UVB radiation from 1974–1985 based on a network of ground-based instruments. However, *Weatherhead et al.* [1997] demonstrated that when accounting for shifts in the data that may have been associated with calibration changes, a slight increase was evident in the same data set. *McKenzie et al.* [1999] reported an increase of 12% in peak summertime erythemal UV radiation at Lauder, New Zealand over a 10-year period in the 1990s. *Fioletov et al.* [2001] calculated trends from measured and reconstructed UVB radiation at three sites in Canada. Summertime measurements from 1989 to 1999 resulted in increases of a few percent per decade. Trends from reconstructed data revealed

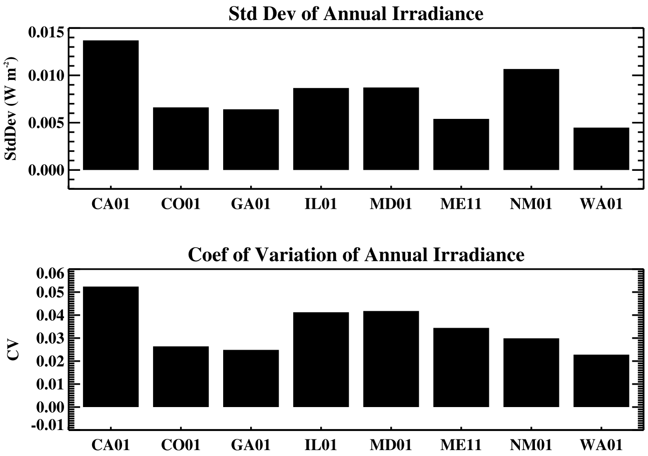

Figure 5. Standard deviation (W m^{-2}) (top) and coefficient of variation (standard deviation divided by the mean) (bottom) showing interannual variability of annual UVB radiation at each site.

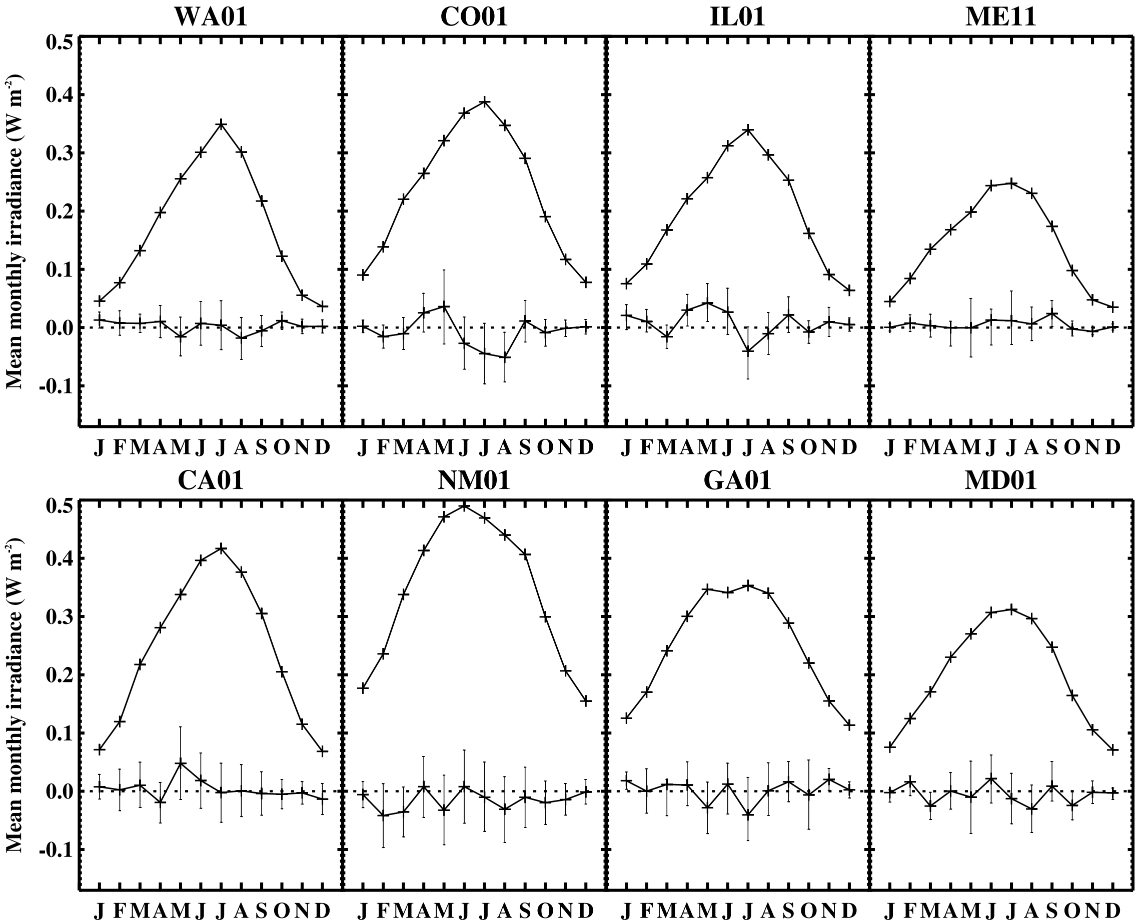

Figure 6. Mean annual cycle of irradiance (W m^{-2}) at each site. For comparison to monthly means, lower curves show total increase by month over the measurement period for each site, as determined from linear least squares regression. Also indicated are the 95% confidence intervals of the trends.

increases of 0–30% from 1979 to 1997. Four sites in Northern Europe generally exhibited positive trends in UVB radiance from about 1980 to the mid-1990s [*Borkowski*, 2000; *Kaurola et al.*, 2000]; increases ranged from 0 to 10% per decade. Observations from 1995 to 2001 in Texas suggested a decrease in peak summer UVB irradiance, however [*Roeder*, 2002]. A recent assessment of studies of surface radiation observations indicated large variability in trends depending on location, period of record, and consideration of clear-sky or all-sky conditions [*Bais and Lubin*, 2007]. Here we report on a consistent, well-maintained, frequently calibrated irradiance time series of ~10 years from eight sites across a broad geographic region.

[41] Several authors have considered the length of time needed to detect a trend at a given site for a given natural variability and autocorrelation [*Glandorf et al.*, 2005; *Weatherhead et al.*, 1998]. For example, *Weatherhead et al.* [1998] estimated autocorrelation, variability (standard deviation), and trends in surface UV radiation from 14 stations in the United States. They concluded that measurements over 25 and 97 years would be required to detect surface UV trends of 2.9 and 0.6% per decade, respectively, given the autocorrelation and variability at the respective stations. Our relatively short time series results in large uncertainty in our estimated trends as reflected by the wide confidence intervals. With continued monitoring in the coming years at the stations examined in this study, trends will become more certain.

[42] In this paper, the physical quantity investigated was instrument-weighted solar irradiance. We do not expect our results to be significantly different if we had considered erythema, a commonly used quantity for studying ozone effects [e.g., *Bais and Lubin*, 2007]. The main difference between these two quantities is that the calibration for erythemally weighted irradiance needs a correction for the spectral mismatch between the instrument response and erythema response, which then requires knowledge of local total ozone at the sites. Both erythemally weighted irradiance and instrument-weighted irradiance are influenced by total ozone, though the radiative amplification factors are different (i.e., for SZA = 30° and 300 DU, $RAF_{ery} = 1.2$ and $RAF_{yes\_uvb} = 0.86$) [*Seckmeyer et al.*, 2005]. Trends in ozone affect the trends in erythema differently than instrument-weighted solar irradiance; however, trends in ozone during this period for midlatitude sites are small [*Fioletov et al.*, 2002]. Given the large uncertainty in the measurements, we do not expect to see trends due to ozone in either erythemally or instrument-weighted irradiance. Therefore our conclusions that the sites do not have significant trends are expected to hold for erythema.

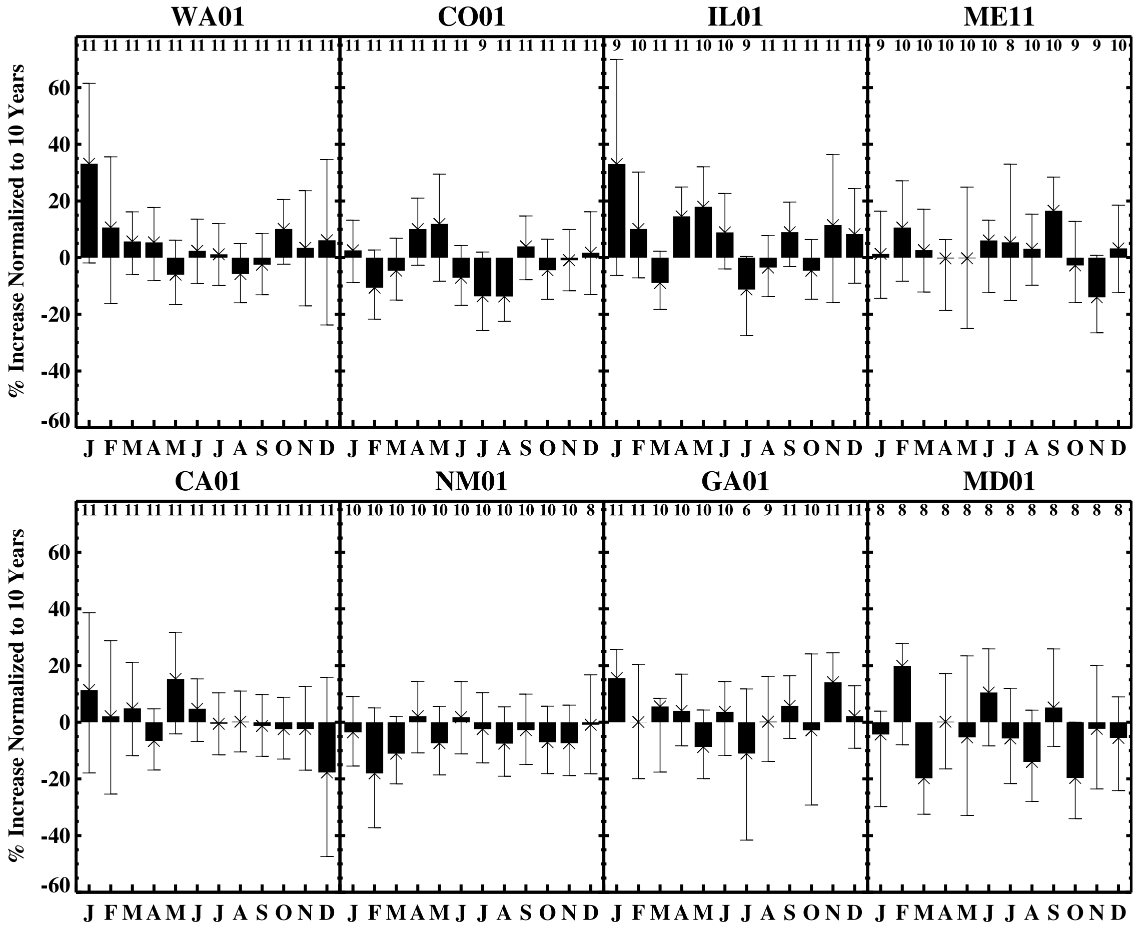

Figure 7. Percentage increases of monthly irradiance at each site normalized to the change in 10 years. Also indicated are the 95% confidence intervals of the trends, and numbers at top indicate number of years of observations.

[43] As noted in the Introduction, different mechanisms affect surface UVB irradiance. Long-term declines in column ozone since 1980 have been well-established globally [e.g., *Fioletov et al.*, 2002]. However, *Fioletov et al.* [2002] report slight increases in ozone derived from ground-based and satellite observations in the latitude band 30–60°N from about 1995–2001. These later increases in ozone during our study period in the region of our network, and the resulting presumed decreases in surface UV irradiance, are consistent with our reported irradiance trends at some sites, though not all. More likely, changes in other properties are responsible for the observed changes in UVB irradiance. Although many monthly UVB irradiance changes occurred in winter or spring and thus may be attributable to changing snow conditions, larger trends also took place in other seasons, eliminating snow as a causal mechanism during these times. Changing aerosol conditions also may have played a role; the increase in UVB irradiance suggests cleaner skies. Further investigation is required to attribute our increases to specific mechanisms with confidence.

[44] Total surface solar radiation (0.3–3 μm) has decreased by 1–3% per decade over the last 50 years as indicated by ground-based measurements [*Cohen et al.*, 2004; *Gilgen et al.*, 1998; *Liepert*, 2002; *Stanhill and Cohen*, 2001], with a possible recovery in the 1990s [*Cohen et al.*, 2004]. Responsible mechanisms include changing aerosol and cloud properties [*Liepert*, 2002; *Stanhill and Cohen*, 2001]. These mechanisms influence UV radiation as well as broadband solar radiation. Inconsistent trends between our results and column ozone at some sites imply that mechanisms that have driven increases in UVB radiation have likely affected total solar radiation as well. We note that although drivers may influence total solar and UVB radiation similarly, quantitative differences also occur such as wavelength dependencies of aerosol and cloud attenuation [*Kylling et al.*, 1997; *Lindfors and Arola*, 2008; *Seckmeyer et al.*, 1996].

[45] The timing of changes in UVB irradiance has important implications for health. We found 10% increases or greater early in the growing season at CA01, CO01, and IL01 that occurred at the time of year when crops are sensitive to increased ultraviolet radiation [*Barnes et al.*, 1995]. This season is also when humans are vulnerable to enhanced exposure to UV radiation. Outdoor activity increases during this time, and reduced protection following decreased wintertime exposure implies heightened risk of photodamage to humans.

5. Conclusions

[46] To analyze 8–11 years of surface UVB irradiance observations across the conterminous United States, we

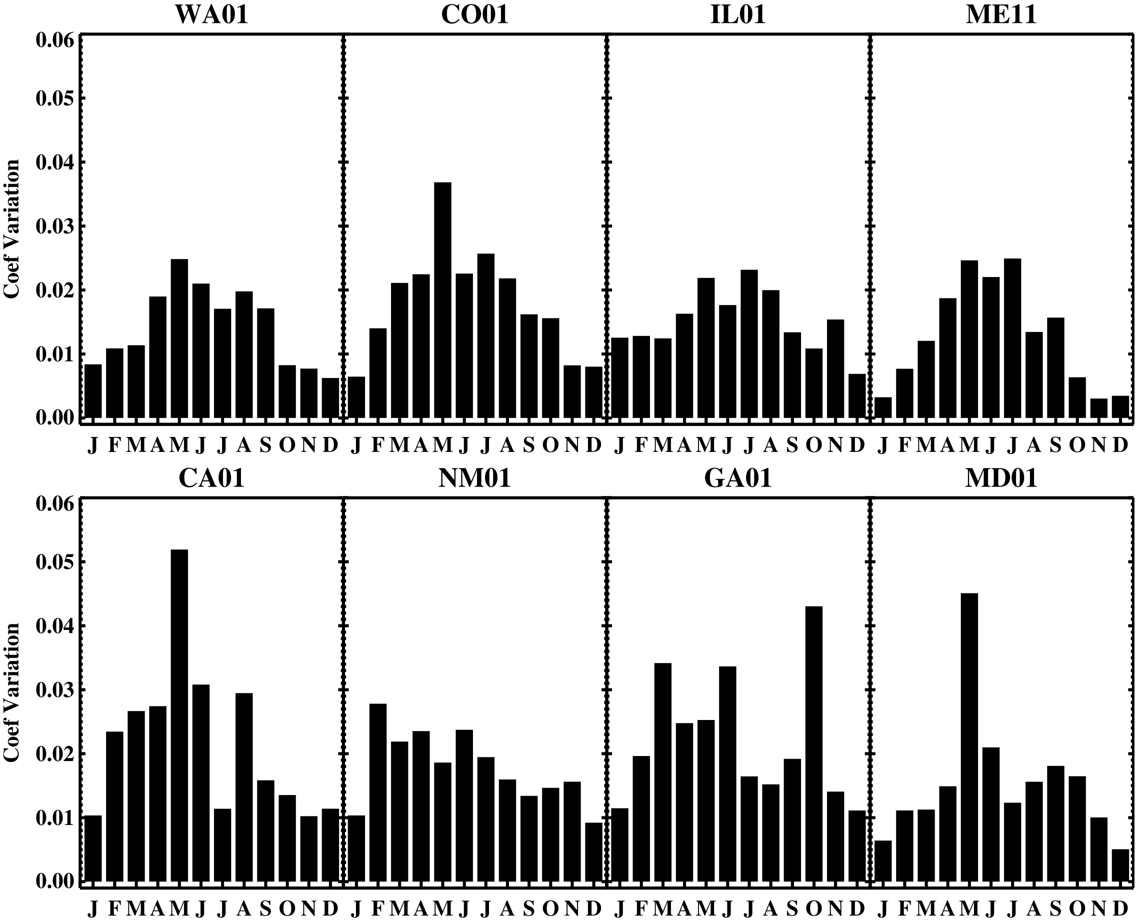

Figure 8. Coefficient of variation of monthly UVB irradiance at each site.

developed a consistent calibration methodology that combined two different techniques applied during different times. Physical adjustments or measured factors calibrated field instruments to laboratory standards, and these standards were then calibrated to spectroradiometers multiple times throughout the study period. Thus instrumentation drifts were well characterized with our methods, greatly reducing the probability of artifacts such as mean level shifts that might introduce spurious trends.

[47] Analysis of annual values of UVB irradiance revealed changes between −5% per decade and +2% per decade. We estimated relatively wide confidence intervals that included 0 (i.e., trends not statistically different from 0) and that reflect the small magnitude of trend values and short time periods of measurements, conclusions supported by other trend analyses [*Glandorf et al.*, 2005; *Weatherhead et al.*, 1998]. Interannual variability of annual irradiance was 2–5% of the mean annual values. Monthly and decadal increases were both positive and negative, with magnitudes often >10%/decade. The largest absolute changes typically occurred in May to September.

[48] Although many studies have focused on the role of ozone in affecting surface UVB radiation, our observed irradiance increases were not always consistent with the reported increase in Northern Hemisphere total ozone during 1995–2004 [*Fioletov et al.*, 2002]. Ozone undoubtedly influences surface UVB radiation; however, with the lack of consistent ozone decline at middle latitudes after the early 1990s, the importance of other geophysical mechanisms affecting UV radiation was enhanced. Likely candidate mechanisms include cloud, aerosol, and snow conditions.

[49] With its 11-year ongoing program, emphasis on high-quality measurements and calibration, and wide geographic distribution across the United States, the USDA UVB Monitoring and Research Program is an excellent monitoring network for assessing changes in UV radiation. Continued measurements by the program will reduce measurement uncertainties, increasing confidence in estimated trends, and improve our understanding of spatiotemporal patterns of UV radiation. In addition to continued monitoring, future research will also focus on characterizing changes in cloud and aerosol properties and snow cover to evaluate their affects on changes in UV radiation.

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