Measurement and Modeling of Ultraviolet-B Irradiance

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Decreases in stratospheric ozone, which have been linked to emissions of manufactured halocarbons, may increase levels of solar ultraviolet-B (280–320 mm) (UV-B) radiation at ground level. The possible harmful effects of increased solar UV-B radiation has heightened interest in measuring and modeling this radiation. The relationship, however, between total column ozone and ground level UV-B irradiance is complex. Air mass, vertical ozone distribution, clouds, haze, and air pollutants all affect the transmission of solar UV-B radiation through the atmosphere (Madronich 1993). Surface albedo also influences the diffuse radiation flux. Furthermore, latitudinal and seasonal variations in surface UV-B irradiance because of stratospheric ozone circulation patterns and solar elevation far exceed the increases in surface UV-B irradiance that might accompany stratospheric ozone depletion in middle latitudes (Frederick 1993). The measurement and modeling of solar UV-B irradiance thus needs to be comprehensive to detect trends and to predict ground level UV-B irradiance under changing atmospheric conditions. In other situations, however, relatively low-cost broadband meters and simplified computer models can accommodate many research needs in agriculture, ecology, and climatology.

Instrumentation to Measure UV-B

Accurate measurements of solar UV-B are technically difficult because solar irradiance decreases five orders of magnitude from 320 to 290 nm, and the region of most interest is the shorter, low intensity wavelengths. Instrumentation must have good wavelength accuracy, sensitivity, high suppression of stray light, and stability to provide reliable data. A variety of instruments are available that meet these requirements.

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Ground-based measurements of UV-B irradiance can be obtained with: high-resolution scanning spectroradiometers that provide full spectral information, optical filter radiometer instruments that measure irradiance at selected narrow wavebands, and broadband meters that provide a weighted measure of UV-B irradiance over the UV waveband. Scanning spectroradiometers typically use mechanically driven diffraction gratings to disperse incident light, which is then detected by a photomultiplier tube. Suppression of stray light is achieved with a double monochromator or a single monochromator and optical filters (Kerr and McElroy 1993). Filter radiometers rely on optical interference filters to block unwanted radiation; whereas, the passband is detected by either a photomultiplier tube (Blumthaler 1993) or a vacuum photodiode (Roy et al. 1989). A filter radiometer can provide spectral information by using a number of narrowband filters that measure specific wavelengths in rapid succession.

Alternatives to the more expensive instruments are illustrated by a broadband instrument such as the Robertson-Berger (R-B) meter (DeLuisi et al. 1992). This instrument uses a magnesium tungstate phosphor in combination with optical filters. Phosphorescence induced by UV radiation is detected by an inexpensive photodiode. The combination of filters and phosphor gives the instrument a spectral response function indicative of human skin erythema.

The best approach for measuring UV-B irradiance depends on the goals of the planned research. General survey instruments suitable for short-term monitoring in agricultural or ecological research will likely be unsuitable for detecting trends in ground level solar UV-B radiation or in detailed modeling applications. In addition, plant researchers using UV-B radiation enhancement techniques are faced with special requirements because the spectral distribution of the sun differs from the UV-B lamps typically used to simulate decreases in stratospheric ozone. If a special weighting function, such as the generalized plant action spectrum (Caldwell 1971), is to be used to interpret the data, an instrument is required that will deliver a well-defined output regardless of the distinct source or proportions of the total irradiance emanating from each source.

To measure trends in UV-B irradiance at the surface of the earth that are attributable to changes in column ozone, high resolution, scanning spectroradiometers provide the most informative data. Spectral irradiance measurements can detect the characteristic wavelength-dependent pattern inherent in such changes (Frederick 1993). For example, measurements obtained with a Brewer spectroradiometer showed an increase in UV-B intensity near 300 nm but not at 324 nm from 1989 to 1993 in Toronto, Canada, that was consistent with measurements of decreased stratospheric ozone over the same period (Kerr and McElroy 1993). Comprehensive measurements of spectral irradiance are being made in the United States, Scandinavia, Europe, New Zealand, Australia, and polar regions using a variety of instruments, although no global, long-term UV monitoring network yet exists (Correll et al. 1992; Wester 1992; Madronich 1993). In general, the data show consistency with measured ozone amounts (Frederick 1993). The accumulating data from these spectral measurements may be valuable for identifying trends and for determining the physical mechanisms (e.g., ozone, aerosols, and cloudiness) responsible for such changes (Madronich 1993).

Optical filter radiometers capable of obtaining high-resolution measurements at several fixed, diagnostic wavelengths may be a less complex and cost-effective method to monitor trends in ground level UV-B than scanning spectroradiometers. Filter radiometers are available from Yankee Environmental Systems Inc (Turners Falls, MA) and International Light Inc (Newburyport, MA). In Sweden, custom-built filter radiometers are used to measure solar irradiance at about 306 and 360 nm to obtain estimates of erythemal UV-B, UV-A, and total column ozone (Wester 1992). Narrow-band irradiance measurements at 307 nm are useful because calculations of solar UV influx by latitude and season have shown that erythemally weighted radiation varies in nearly the same way as radiation at 307 nm (Johnson et al. 1976). A 4-nm half-bandwidth interference filter centered at 303 nm or a 4-nm half-bandwidth low pass filter centered at 305 nm will theoretically indicate UV-B irradiance weighted by the Caldwell (1971) generalized plant-action spectrum normalized to 300 nm. Simulated filters convolved with 168 actual spectroradiometer scans from several locations and times confirm an acceptable linearity between transmitted radiation and plant-action weighted irradiance whether the source is the sun, UVB-313 lamps (Q-Panel Co, Cleveland, OH), or a combination of the two.

Broadband meters have been widely used to monitor trends in solar UV-B radiation, although their efficacy in this role is controversial. A network of R-B meters was established in the United States in the early 1970s, with later additions in Australia and Europe, to measure solar erythemal radiation on a continuous basis. Evaluations of long-term measurements obtained with R-B meters, however, have shown both a decline in solar UV-B irradiances at eight R-B network stations from 1974 to 1985 (Scotto et al. 1984) and an increase in clear-sky solar UV-B irradiance at a high-altitude site in the Swiss Alps since 1981 (Blumthaler 1993). Both reports have been criticized because they reported trends in solar UV-B radiation that were in the opposite direction or larger than that expected from the changes in column ozone measured over the same period (Frederick 1993). Various factors (e.g., instrument drift, improper calibrations, changes in air pollutant levels, and large variability in the data) have been offered and in some cases refuted as explanations (DeLuisi et al. 1992; Blumthaler 1993; Frederick 1993; Madronich 1993). For example, recent evaluations of several R-B meters used in the network found that the instruments and spectral responses were basically stable, and that the calibration procedures and temperature drift did not account for the downward trend in UV-B radiation levels observed by Scotto et al. (1988) (DeLuisi et al. 1992; Kennedy and Sharp 1992). A comparison between clear-sky R-B data and computed R-B measurements based on Dobson ozone measurements at two sites in the United States (Bismark, ND and Tallahassee, FL) showed good agreement during the summer months (Frederick and Weatherhead 1992). However, the analysis revealed a downward trend in R-B data during the winter that was not supported by Dobson ozone data and could not be explained.

Although broadband R-B meters may not be adequate for unambiguously detecting the effects of stratospheric ozone depletion, the meter is useful for many applications in agriculture, forestry, ecology, and climatology to provide ground-based measurements of UV-B radiation. Its use in this role is particularly important in UV-B enhancement studies conducted in the field because accurate estimates of UV-B exposure and the corresponding simulated ozone depletion can be determined. In our studies, an R-B meter was used to monitor solar UV-B radiation continuously and a portable erythemal meter with a detachable sensor (Model 2D, Solar Light Co Inc, Philadelphia, PA) was used daily to measure and adjust the supplemental UV-B irradiance provided by lamp banks (Booker et al. 1992a; Miller et al. 1994). Modified versions of the R-B meter with improved spectral response, temperature stability, and data acquisition systems are available from Solar Light Co Inc (Philadelphia, PA), Yankee Environmental Systems Inc (Turners Falls, MA), VITAL Technologies (Ontario, Canada) and others. A broadband meter called the YMT sensor, similar in design to the R-B meter, has a spectral-response function that approximates the generalized plant action spectrum, which is desirable for monitoring solar UV-B radiation and controlling UV-B supplementation systems in plant research projects (Yu et al. 1991).

Ultraviolet-B Models

Modeling solar UV irradiance can be helpful for understanding the transmission of solar UV-B radiation through the atmosphere and for deducing ground level UV-B irradiance from measurements of column ozone and other pertinent atmospheric and surface factors. In addition, UV-B supplementation experiments require a model that relates treatment exposures to the simulated stratospheric ozone depletion. A number of radiative-transfer models have been developed that vary in approach and complexity (Björn 1989; Frederick and Snell 1990; Madronich 1993). A model developed and revised by Green (1983) has been widely used (Rundel 1986; Correll et al. 1992; Blumthaler 1993). Björn and Murphy (1985) and Björn (1989) encoded the revised algorithms, modified the reflection coefficient routines, added several weighting functions, and included an additional feature that allowed internal generation of column ozone values for the northern hemisphere. More recently, we expanded the Björn and Murphy (1985) and Björn (1989) codes to increase the flexibility and usefulness of the program (Fiscus and Booker 1993). Routines to allow yearly and daily irradiance calculations were added. The model also allows the user to input special weighting functions and annual files of relevant environmental data (e.g., humidity, barometric pressure, aerosols, and most importantly, column ozone data obtained from the TOMS instrument flown on the Nimbus-7 satellite (McPeters et al. 1993) or from any other source).

Comparisons between measured and computed irradiances showed that the revised Green-Björn and Murphy model predicted solar spectral irradiance in the UV-B region with accuracy (Björn and Murphy 1985; Björn 1989). Good agreement between the Green-Björn and Murphy model and other UV-B models has also been observed (Björn 1989). In addition, output from the Green-Björn and Murphy model weighted by the spectral response function of the R-B meter was highly correlated with data from the R-B network (Björn 1989).

We have found that output from the Green-Björn and Murphy model weighted by the spectral response function of the Model 2D meter sensor (Solar Light Co), which was designed to simulate an erythemal action spectrum (Parrish et al. 1982), fit the clear-sky boundary of our R-B data very well. This is understandable because spectra weighted by the Model 2D sensor and R-B meter spectral response functions are similar in shape. The daily counts from the R-B meter were converted to plant-action spectrum-weighted irradiances normalized to 300 nm (UV-B_{BE}) (Caldwell 1971). The conversion was done as previously described (Fiscus et al. 1994) by using the ratio of the Model 2D sensor-weighted irradiance to the UV-B_{BE} irradiance calculated from the model. This ratio was computed for each day of the year using TOMS ozone column data for that day. The validity of this approach was confirmed by comparisons between the derived UV-B_{BE} irradiances and calibrations of our R-B meter done with a scanning spectroradiometer on 5 days in 1990-1991 (Booker et al. 1992a). The comparison showed that the mean (± SD) calculated calibration (2.16 ± 0.10 R-B counts = 1 J/m^2 UV-B_{BE}) agreed with the mean spectroradiometer calibration (2.10 ± 0.14 R-B counts = 1 J/m^2 UV-B_{BE}) within 3%.

We found that UV-B_{BE} irradiance computed by the model when TOMS column ozone data were input compared well with measurements of solar UV-B_{BE} radiation obtained with our R-B meter over several years (Fig.1). The model accurately tracked the outer (clear sky) envelope of the data. The daily R-B data, however, are highly variable, which has been attributed mainly to cloudiness (Frederick and Snell 1990). To further explore the ability of the model to compute accurately daily irradiance at ground level, we examined several ways to compensate for the source of variability in the data set.

Ultraviolet-B Model Validation

The effect of fractional cloud cover on solar UV-B influx has been approximated by:

$$F_s/F_0 = (1 - 0.056\,C)\,, \qquad (1)$$

where F_s is the radiation flux at the surface, F_0 is the radiation flux for clear skies, and C is the average cloud cover in tenths of the sky (Johnson et al. 1976). Similar approaches have been used in other model calculations (Björn 1989; Madronich 1993).

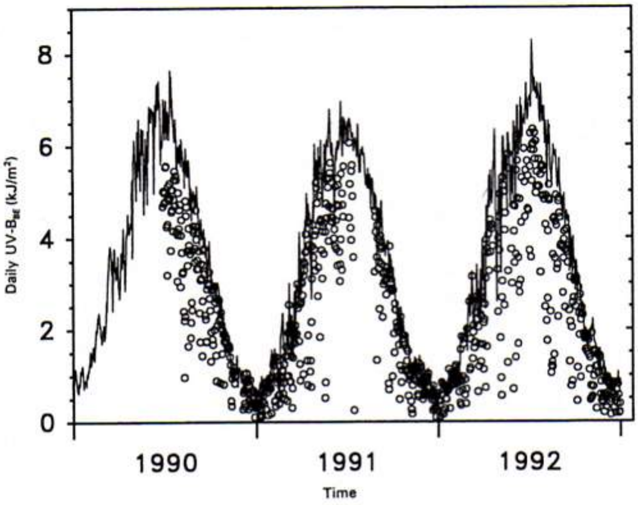

Fig. 1. Daily measured and modeled plant-action spectrum weighted UV-B (UV-B$_{BE}$) irradiance from 1990 to 1992 at Raleigh, NC (35.75°N, 78.67°W). Measurements were obtained with an R-B meter (O) and converted to UV-B$_{BE}$ irradiance as described in the text. User input data for the revised Green-Björn and Murphy model (—) were: ozone column – TOMS data; environment – rural; ground cover – green farmland; barometric pressure 1020 mb; relative humidity 0.50; aerosols 0; action spectrum – generalized plant-action spectrum normalized to 300 nm

We used estimates of average cloud cover (in tenths) made daily by the National Weather Service at a local airport to calculate F_0 for each day in 1992 using the daily UV-B$_{BE}$ irradiance measured by our R-B meter as F_s. The UV-B$_{BE}$ data adjusted for cloud cover were then compared with model calculations (Fig. 2). The average fit between the UV-B$_{BE}$ data adjusted for clouds and the model was improved, although the data remained highly variable (Table 1). Adjusting the irradiance on the basis of cloud cover increased the values of measured UV-B$_{BE}$ irradiance data in 1992 from an annual mean ratio of 0.71 ± 0.24 (± SD) of clear-sky calculations to 1.10 ± 0.30 of the clear-sky maximum. Using various combinations of cloud-cover estimates made at 3-h intervals each day at the airport did not noticeably improve the fit. Estimates of average cloud cover provided only a rough approximation of the attenuation of solar UV-B irradiance by clouds. Additional comparisons between average cloud cover and minutes of sunshine recorded daily at the airport did not suggest that estimates of solar UV-B radiation at ground level would be substantially improved by incorporating sunshine data into attenuation computations.

Measurements of visible radiation from 400 nm to 700 nm (photosynthetically active radiation, PAR) might provide an independent index of factors other than ozone that attenuate solar UV-B irradiance (e.g., clouds and aerosols). Minimal wavelength dependence in the transmitted radiation would be expected to arise from passage through clouds (Madronich 1993), and one study showed

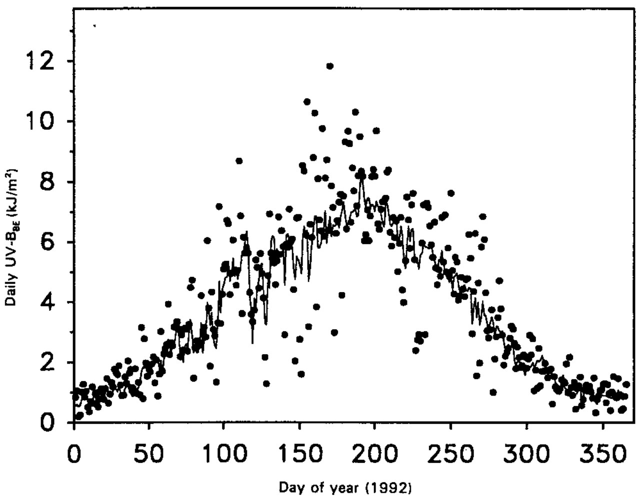

Fig. 2. Daily measured UV-B_{BE} irradiance adjusted using average daily cloud cover data (SC) and modeled UV-B_{BE} at Raleigh, NC. User input data for model calculations were the same as those described in Fig. 1 (— Green-Björn and Murphy; • SC adjusted R-B data). Note the change in scale on the y axis compared with Fig. 1

Table 1. Average ratios (± SD) between measured and modeled UV-B_{BE} irradiances for 1992 at Raleigh, NC (35.75°N, 78.67°W). Measurements were obtained with an R-B meter and converted to UV-B_{BE} irradiance as described in the text. User input data for the revised Green-Björn and Murphy model were: ozone column – TOMS data, environment – rural, ground cover – green farmland, barometric pressure 1020 mb, relative humidity 0.50, aerosols 0, and action spectrum – generalized plant-action spectrum normalized to 300 nm

Comparison	Ratio±SD
Measured UV-B_{BE} / modeled UV-B_{BE}	0.71 ± 0.24
UV-B_{BE} adjusted for cloud cover / modeled UV-B_{BE}	1.10 ± 0.30
UV-B_{BE} adjusted with PAR / modeled UV-B_{BE}	1.03 ± 0.09

that global irradiance was only slightly more attenuated than erythemal irradiance as cloudiness increased (Blumthaler 1993). The PAR instruments are also inexpensive and widely available; therefore, this seemed to be a reasonable approach.

The first step was to establish an empirical relationship between PAR and UV-B_{BE}. A linear model could be fit to the relationship between daily UV-B_{BE} and daily PAR for each month of the year in 1992, but the slopes (dUV-B_{BE}/dPAR) of the lines changed over the year (Fig. 3). The slopes increased during the spring, remained fairly constant from April through September, and then decreased again. This pattern was attributed to seasonal changes in column ozone and solar elevation that attenuated UV-B_{BE} irradiance relatively more than PAR (Blumthaler 1993). Because the seasonal changes were large, we decided to use

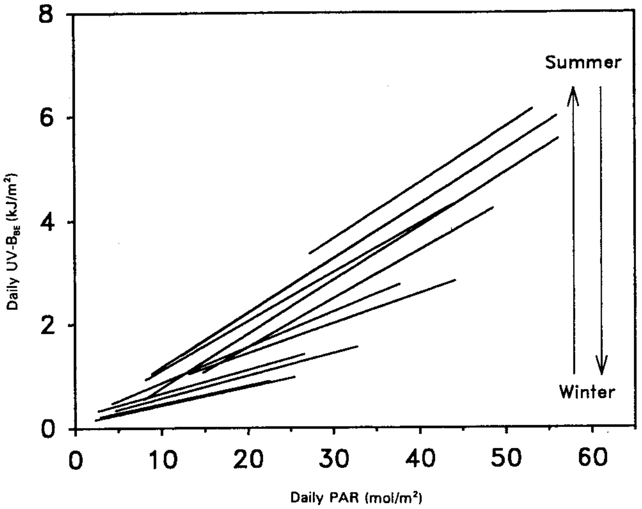

Fig. 3. Linear regression models of the relationship between measured UV-B_{BE} irradiance and PAR for each month of 1992 (Raleigh, NC)

the slopes of the linear models for each month in our calculations. In addition, a derivation of PAR attenuation was obtained to serve as an index factor. Maximum daily PAR (PAR_{MAX}) was approximated by plotting daily PAR, drawing an outer envelope to the data by inspection, and modeling the envelope with a polynomial. The PAR_{MAX} could then be estimated for each day. The use of PAR measurements to estimate attenuation of solar UV-B_{BE} irradiance was expressed as:

$$\text{UV-B}_{BE\,MAX} = \text{UV-B}_{BE} + k\,(\text{PAR}_{MAX} - \text{PAR})\,, \tag{2}$$

where UV-$B_{BE\,MAX}$ is the UV-B_{BE} irradiance for clear skies, UV-B_{BE} is the measured UV-B_{BE} irradiance at the surface, k is the slope of the linear model for UV-B_{BE} versus PAR for the appropriate month, and PAR_{MAX} is the calculated maximum daily PAR.

The fit between the UV-B_{BE} irradiance data adjusted by this approach and the model was significantly improved (Fig. 4, Table 1). There was a short interval from day 180 to day 220 where the adjusted data were below the model calculations, probably because of an underestimate of the PAR_{MAX} boundary line in this region. Nonetheless, there was good overall agreement between the data and model calculations. The incorporation of concurrently measured visible radiation data, as an index of solar UV-B_{BE} attenuation, increased the annual mean ratio of the measured-modeled data to 1.03 ± 0.09 of the clear-sky calculations. Compared with UV-B_{BE} data adjusted with average daily cloud cover, UV-B_{BE} data adjusted with PAR measurements approximated model calculations more closely and with much less variability.

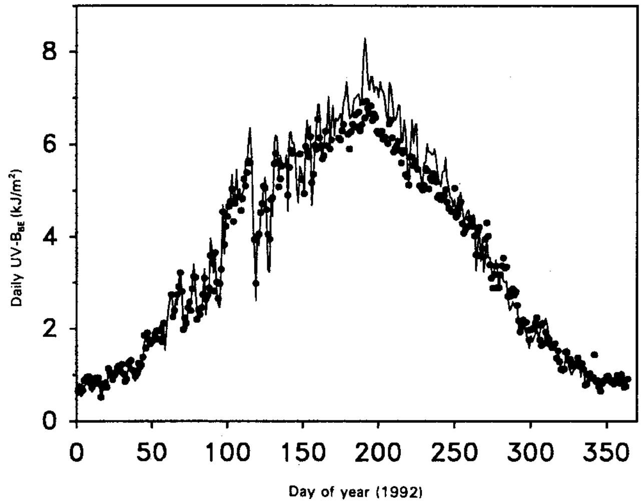

Fig. 4. Daily measured UV-B$_{BE}$ irradiance adjusted using daily PAR data and modeled UV-B$_{BE}$ irradiance for 1992 at Raleigh, NC. User input data for model calcuations were the same as those described for Fig. 1 (— Green-Björn and Murphy; • PAR adjusted R-B data)

The reason why daily estimates of average cloud cover failed to serve as a good indicator of attenuation was apparent from a plot of average cloud cover versus PAR/PAR$_{MAX}$ (Fig. 5). The data are extremely variable, especially for high values of cloud cover. An index of solar UV-B$_{BE}$ irradiance attenuation based on PAR was far more resolved and informative.

This analysis provided additional evidence that the estimates of clear sky solar UV-B$_{BE}$ irradiance computed by the revised Green-Björn and Murphy model are reasonably accurate. It is important to establish the validity of the model because it allows the user to interchange measured irradiance data among weighting functions. For example, irradiance can be monitored with a broadband meter with one spectral response function and then the model can be used to convert the data to another weighting function. Data can be gathered with an erythemal meter and then converted to values weighted by the generalized plant-action spectrum. Estimates of clear sky irradiance computed by the model also allow for more accurate determinations of the fraction of solar UV-B irradiance attenuated by clouds and aerosols. This is important to consider when conducting and evaluating UV-B enhancement studies.

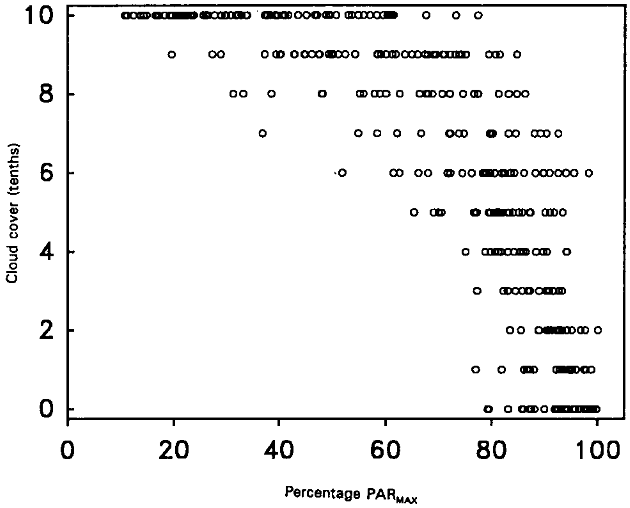

Fig. 5. Daily average cloud cover (in tenths) versus percentage of maximum PAR (Raleigh, NC, 1992)

Conclusion

A variety of instruments are available to measure solar UV-B irradiance, although their suitability depends on research goals. High resolution, scanning spectroradiometers provide the most informative data for detecting trends in solar UV-B irradiance. The United States Department of Agriculture plans to establish a monitoring network in the United States to detect trends in UV-B irradiance. High-resolution spectroradiometers will be used in conjunction with a network of broadband or multiband filter meters (with adequate sensitivity at wavelengths of about 300 nm) to detect trends of 5% per decade in UV-B irradiance at ground level (Gibson 1992). Specifications for these research-grade instruments are so stringent that existing instruments must be modified to meet the requirements. At the other end of the scale, however, relatively low-cost broadband meters and simplified computer models can accommodate many research needs in agriculture and ecology. We have further shown that concurrent measurements of visible radiation can provide valuable ancillary information when solar UV-B radiation is monitored and modeled. Monitoring solar UV-B radiation and developing models continue to be essential activities to provide the data and tools needed to assess the impact of stratospheric ozone depletion and global climate change on biological systems.

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Björn and Murphy model can obtain a copy of our UVB program from E.L. Fiscus, USDA-ARS, 1509 Varsity Drive, Raleigh, NC 27606, USA.

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