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IMPACT OF SKY CONDITIONS ON ERYTHEMAL UV-B EXPOSURE UNDER TREE CANOPIES

Gordon M. Heisler
USDA Forest Service, Syracuse, New York

Richard H. Grant
Purdue University, W. Lafayette, Indiana

Wei Gao
Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado

1. INTRODUCTION

Solar ultraviolet (UV) radiation at the Earth's surface has many implications for human health. There appear to be complex relationships between skin cancers and sun exposure (Heisler and Grant 2000a, Heisler and Grant 2000b, Vitasa, et al. 1990). These health effects may have been exacerbated by depletion of the stratospheric ozone layer and attendant increases in UV-B (320-280 nm) radiation (de Gruijl 1995), because average UV-B irradiance has increased about 4 to 6% in mid-latitudes since the 1970's (Madronich, et al. 1998). However, changes in habits of recreation, dress, and the increased value placed on a "tan" are evidently largely to blame for most of the increases in skin cancer rates in recent decades (Heisler and Grant 2000a).

The health impact of solar UV depends on the environmental conditions as well as human habits. Researchers have made significant improvements in the prediction of open-environment exposure of surfaces at various slopes (Grant 1998, McKenzie, et al. 1997, Parisi and Wong 1994). However, most people spend much of their outdoor time in environments in which there is significant obstruction to sky and direct sun by buildings and trees. Prior studies have shown that the irradiance at pedestrian heights is significantly influenced by canopies of trees and buildings (Grant 1997, Grant and Heisler 1996, Grant, et al. 2002, Heisler, et al. 2003a). Tree cover in most urban areas is substantial; in a survey study of the tree cover of many cities, Nowak and coworkers (1996) indicate that tree cover in residential areas ranges from 48% in forested climates, to 27% in grassland climates, and 11% in desert climates.

Human exposure to UV-B radiation and the effects of shading objects have often been described for clear sky conditions. Although survey measurements showed that cloud cover influences the relative exposure to UV-B radiation in shaded environments (Moise and Aynsley 1999); it is well known that cloud cover does not greatly reduce the UV irradiance until the cover is opaque and nearly overcast (Barton and Paltridge 1979, Frederick and Steele 1995, Grant and Heisler 2000). However, we expect the type, thickness, and fractional cover of clouds to cause variation in UV-B irradiance beneath trees; especially because the irradiance under partly cloudy skies is affected by scattering off the sides of clouds (Mims and Frederick 1994).

One approach to evaluating cloud cover effects on UV-B exposure of people under tree canopies in different neighborhoods is to model the relative irradiance beneath tree canopies compared to above canopy irradiance and then to use measured or modeled UV-B irradiance above the canopy to approximate the irradiance under the canopy. The above-canopy UV-B irradiance can be derived from monitoring networks such as that of the United States Department of Agriculture UV-B Radiation Monitoring Program (Bigelow, et al. 1998) or from other UV-B measurements (Heisler, et al. 2003b). A recent model of UV-B irradiance above canopy, including cloud effects is also available (Madronich, et al. 1998), and in this paper we use this model and a model of radiation transmission through tree canopies to estimate UV-B exposures under tree canopies in the Baltimore, MD area under variable cloud conditions and tree cover.

2. METHODS

The model developed to predict UV-B irradiance below vegetation canopies is an adaptation of a 3-D relative irradiance model (Gao 1997, Gao, et al. 2002, Grant, et al. 2002). This model assesses the UV-B irradiance at a point below a canopy given sky conditions and a canopy consisting of a finite number of ellipsoidal crowns that act as discrete scattering volumes. The foliage in the crowns is characterized by a single foliage density. In our modeling for this analysis, the probability of penetration of sky diffuse radiation was computed using separate hemispherical sky radiance distribution models for cloud-free skies (Grant, et al. 1997a), partly cloudy skies (Grant, et al. 1997b), and overcast skies (Grant and Heisler 1997).

To approximate the relative irradiance (I_r) under a canopy of essentially infinite extent, we modeled an 11 X 11 array of regularly spaced tree crowns and averaged irradiance over a grid below the central four crowns. We carried out this analysis for solar zenith angles of 15°, 30°, 45°, and 60° and the National Weather Service cloud cover classes of CLeaR (<1 octa), FEW (1-2 octas), SCaTtered (3-4 octas), BroKeN (5-7 Octas), and OVerCast (8 Octas). We interpreted average cloud cover in octas (*C*) from the cloud classes accordingly: CLR, *C*=0; FEW, *C*=1.5; SCT, *C*=3.5; BKN, *C*=6; and OVC, *C*=8. Diffuse fractions (*D*) for each solar zenith angle (θ) and cloud cover class were based on an empirical equation of Grant and Gao (2003) that represents the average mean *D* as a function of cloud cover and solar zenith angle under the atmospheric conditions across the continental United States. This estimated *D* and is consequently independent of ozone column depth or atmospheric aerosol thickness.

The relative irradiance under the canopy was defined as:

$$I_r(C,\theta,m,\delta) = \frac{I(C,\theta,m,\delta)}{I_o(C,\theta)}, \qquad [1]$$

where I is the below canopy UV-B irradiance, I_o is the above-canopy UV-B irradiance with clouds; *m* is tree cover fraction, and δ represents either the shaded, sunny, or all locations in the array. Crowns were assumed to have high leaf density so that UV-B radiation penetrated through the canopy between individual crowns only. We then estimated the mean spatial irradiance below the canopy relative to the clear sky irradiance above the canopy according to:

$$I_s(C,\theta,m,\delta) = \tau_c I_r(C,\theta,m,\delta) \qquad [2]$$

where τ_c is a cloud transmittance for UV-B valid to θ = 60° according to Kuchinke and Nunez (1999):

$$\tau_c = I_o(C) / I_o(0) \qquad [3]$$

The relationship between solar zenith and cloud-free sky erythemal UV-B irradiance (McKinlay and Diffey 1987), $I_{ery}(0,\theta)$, was based on simulations of UV-B irradiance by the TUV model of Madronich (1998) (http://www.acd.ucar.edu/TUV/) with total ozone column thickness (TOC) of 280 DU (Dobson units), surface altitude of 0.10 km and surface albedo of 0.10. The erythemal UV-B irradiance under the canopy was estimated according to:

$$I(C,\theta,m,\delta) = I_{ery}(0,\theta) \cdot I_s(C,\theta,m,\delta) \qquad [4]$$

We used the canopy array model to predict the UV-B dose for several land uses in the metropolitan Baltimore, MD, USA area. For each land use, the relative UV-B irradiance on people was estimated from the spatial average I_s below the array of spherical tree crowns with *m* equivalent to the tree cover fraction reported for the particular land uses in a field survey in Baltimore (Nowak, et al. 2004). The I_s over the range of solar zenith angles was calculated with the below-canopy grid at the height of the crown base (assumed pedestrian height) of the array of spherical crowns.

The estimates of the erythemal dose on people in the Baltimore land uses were made for the 10AM to 2PM interval over the summer period of May through August of 2001, 2002, and 2003. The areal average I_s for a given solar zenith angle and tree cover fraction provided the relationship between the above and below canopy irradiance for the tree array. The cumulative dose for the 4-hr period centered on solar noon was described using the minimum erythemal dose (MED) of CIE-weighted irradiance (The MED is minimum UV-B dose that causes reddening of light human skin (McKinlay and Diffey 1987) The mean hourly irradiance corresponding to 1 MED (201 $\mathrm{Jm^{-2}}$) is 0.056 $\mathrm{Wm^{-2}}$.) We assessed the effect of accounting for cloud cover on the 4-hour erythemal dose by comparing the estimated dose under cloud-free conditions to that under cloud cover.

3. RESULTS AND DISCUSSION

3.1 *Variation in I_s with Cloud Cover*

Using the 3-D array relative irradiance model, we first derived the spatial mean relative irradiance I_r under cloudy skies according to Eq. 1 and then adjusted I_r to account for changes in the above canopy irradiance from clear skies using Eq. 2 and the ratio τ_c for cloud transmittance in Eq. 3. The spatial mean I_s of the whole shady and sunlit areas below the canopy is influenced by the cloud cover (Figure 1). Shady and sunlit areas are defined by the direct beam shade pattern. The I_s across the below-canopy domain decreased with increasing cloud cover in accordance with the decrease in above-canopy irradiance with increasing cloud cover. However, the relative exposure under CLR, FEW, and SCT cloud conditions were similar (Figure 1). The transition from essentially clear sky conditions to OVC sky conditions occurred for BKN cloud cover. With clear skies and with *m = 0.5,* spatially averaged irradiance below canopy ranges from about 30 to 40% of above-canopy UV-B irradiance.

In contrast to I_s over the overall area (Figure 1), I_s in shaded areas of the array decreased with decreasing θ (Figure 2). The anomalous I_s values evident at *m* near 0 in Figure 2 are an artifact of the tree crown dimension and estimation grid spacing and do not indicate a fundamentally different radiation regime from that at higher *m*. Even discounting these anomalous values, the I_s in these shaded areas with low *m* is still 30% to 40% of the above-canopy irradiance with clouds less than OVC and θ up to 30° (Figure 2). This situation is equivalent to a person being in the shade of a small single tree crown and having a large view of the sky.

For low cloud cover, especially for SCT clouds at θ = 60°, *D* is greater than with clear skies, and thus the mean I_s in shaded areas is greater that under clear skies. The influence of the cloud cover on the mean areal I_s in the shaded areas was greatest for overcast skies.

In order to estimate actual rather than relative irradiance below canopies, we first used largely empirical means to fit nonlinear equations to the relationships in Figures 1 and 2. For the mean of the sunlit and shaded portions, exposure regime can be modeled similarly to that done for clear skies (Heisler, et al. 2003a), which resulted in the relationship for relative irradiance:

$$I_r = 1 - m - (\theta^{0.711}/5.05)\sin(\pi m).$$

In this study, the multivariate regression of the mean areal I_s of the center of the 11 x 11 array of trees for solar zenith angles of 15°, 30°, 45°, and 60° against the calculated tree cover fraction and solar zenith angle resulted in relationships of the form

$$\bar{I}_s(C,\theta,m,all) = a(1-m) - (\theta^b/c)\sin(\pi m), \quad (5)$$

with different parameters for differing cloud cover (Table 1). For CLR and FEW cloud conditions, one equation fit the combined data. For OVC conditions, the relationship did not vary with θ, so the exponent "*b*" was 0. The fit of the empirical modeled values to the 3-D relative irradiance geometric model output is indicated in Figure 1.

For average in-shade locations, the intercept changes with θ, so both the straight-line part in the first right-hand term and the curvature in the second right-hand term are functions of θ, for a model of the form:

$$\bar{I}_s(C,\theta,m,shaded) = (a + b\theta^c)(1-m) - (\theta^d/e)\sin(\pi m). \quad (6)$$

The model coefficients associated with equation (6) for the different cloud conditions are shown in Table 2. The fit of the empirical modeled values to the 3-D relative irradiance geometric model output is indicated in Figure 2.

Table 1. Coefficients for spatial-mean exposure prediction by Eq. 5.

Cloud cover	*a*	*b*	*c*
CLR and FEW	1.000	0.598	4.77
SCT	0.931	0.447	5.02
BKN	0.683	0.252	7.00
OVC	0.368	0	14.87

Table 2. Coefficients for shaded-area exposure predicted by Eq. 6.

Cloud cover	*a*	*b*	*c*	*d*	*e*
CLR and FEW	0.261	0.407	1.50	0.969	7.24
SCT	0.315	0.527	2.97	1.79	5.72
BKN	0.259	0.370	2.63	1.82	7.78
OVC	0.060	0.316	0.970	1.86	13.63

3.2 *Variation in Erythemal Irradiance with Cloud Cover*

The below-canopy spatial-mean irradiance of erythemal radiation was determined by applying the TUV-modeled erythemal irradiance above canopy to the modeled below-canopy relative irradiance from Eq. 5 (Figure 1). For example, the irradiance above the canopies under OVC skies with TOC = 280 DU ranged from approximately 2 MED per hour (approx. 0.112 $\mathrm{Wm^{-2}}$ for an hour) with solar zenith angle of 15° to approximately 1 MED per hour with a solar zenith angle is 45°. Within the canopy of vegetation, exposure is quite low under these nominally overcast skies (Figure 3). Spatial mean erythemal exposures for CLR to SCT cloud cover, BKN, and OVC under a 20% canopy cover environment correspond to approximately 3, 2, and 1 MED per hour respectively when the solar zenith angle is 30° (Figure 3). Spatial mean erythemal exposure under broken clouds is approximately halfway between that for clear skies and overcast skies.

There is greater similarity in exposures in the shade under the canopies across the 15° to 45° solar zenith angles than is evident for the domain as a whole (Figures 3 and 4). The slightly greater erythemal irradiance in the shade under partly cloudy skies (less than 50% cloud cover) than under clear skies is a consequence of increased diffuse fraction with increasing cloud cover while the global irradiance changes little. The exposure in the shaded regions of the 20% canopy was approximately 1 MED across the 15° to 60° solar zenith angle range for all sky conditions except overcast skies (Fig. 4). As in Figure 2, the anomalous I_s values evident at low *m* in Figure 4 are an artifact of the tree crown dimension and estimation grid spacing and not indicating a fundamentally different radiation regime from that at higher *m*.

These results indicate that the relative effectiveness of tree shade to reduce exposure to UV-B irradiance is generally not dependent on the cloud cover except under overcast skies.

3.3 *Baltimore UV-B Exposure*

We estimated mean erythemal irradiance and the subsequent mean exposure of people over time in locations with trees in Baltimore, Maryland using equations 5 and 6, the erythemal above-canopy irradiance, assumption of TOC = 280 DU, and remotely-sensed tree cover information. The TOC of 280 DU is a relatively low value compared to long-term averages, so the predicted UVB exposures are near maximum values. The tree-cover-density estimates were determined for four land-use classes that are commonly used by pedestrians (Table 3). The corresponding exposures for people moving in the tree space over the 4-hr noon window of time are indicated in Table 3. In Baltimore, the high-building-density residential class includes a large proportion of row houses; the definition of "high-density" is more than 8 dwelling units per acre (more than 20 units per hectare). Mid- and low-density residential land uses have mostly detached single housing units with less than 8 units per acre. Institutional land uses include schools, colleges, and churches. Urban open land has few or no constructed structures, and includes parks, cemeteries, and golf courses.

The UV-B protection factors (UPF, the relative time that a person could remain in a location and receive 1 MED of exposure) for the tree canopies in Baltimore were on average 2.0 for the entire area under tree canopies and 4.0 for shaded areas. The mean erythemal exposure across the various land use classes over the 4 hours was 4.7 MED. The mean erythemal exposure in shaded areas was 2.2 MED (Table 3). Exposures in the high-building-density residential land-use class were 27 to 29% higher than in the low to

Table 3. Land uses of Baltimore, Maryland and predicted exposures to UV-B from 10 AM to 2 PM considering clouds and tree cover averaged over the months of May through August of 2001, 2002, and 2003.

			Mean UV-B Exposure (MED)		Mean UV-B Exposure in shade (MED)	
Land use class	% area in Baltimore	Tree cover, the variable *m*	Actual cloud cover	Cloud-free	Actual cloud cover	Cloud-free
High-density residential	28	20	5.00	7.00	2.28	2.74
Mid- and low-density residential	20	32	3.88	5.51	1.80	2.11
Institutional	9	13	5.64	7.84	2.56	3.10
Urban open	7	26	4.40	6.20	2.00	2.36

medium density residential land use class. Recreational activities in "open" urban land are predicted to result in approximately 1 MED/hr exposure, slightly more than mid- to low-density residential areas and slightly less than the high-density residential areas.

Typically, exposures were 40% higher assuming no clouds for the spatial mean exposures and 20% higher for the mean exposures in the shade (Table 3). The relative effect of including cloud cover in the exposure estimate varied by year with the smallest effects in 2001 and the greatest in 2002.

Receptor surfaces on the human body have a wide range of orientations and the estimates described here apply only to horizontal surfaces such as an exposed vertex of the head. The areas of the body with greatest exposure potential are the face, shoulders, and arms. Exposure to the face in sunlit conditions can be estimated using corrections for various orientations and parts of the head developed by Kimlin and Parisi (2000).

4. SUMMARY AND CONCLUSIONS

The erythemal UV exposure in the open under skies with 4 octas or less of cloud cover is not remarkably different from that under clear skies. Changes in the erythemal exposures from clear sky to overcast sky conditions occur when the cloud cover is between 5 and 7 octas (broken clouds). Consequently, in this study the UV-B protection afforded by tree canopies under partly cloudy skies (50% or less cloud cover) was found to be similar to that for clear sky days except for zenith angles greater than 45°.

With solar zenith angles from 15° to 45° there is greater similarity in erythemal UV exposures in shade under tree canopies than across the spatial average of the below-canopy domain as a whole. A slightly greater erythemal irradiance in the shade was predicted under partly cloudy skies (less than 50% cloud cover) than under clear skies -- a consequence of increased diffuse fraction with increasing cloud cover while the global irradiance changes only slightly. Further experiments are needed to verify this effect.

The consideration of the cloud cover on estimating the erythemal exposure for people in Baltimore strongly influenced the predicted exposure. Not including the cloud cover in estimating exposures resulted in a 40% over-estimate across the entire under-canopy space and a 20% over-estimate in the shaded areas under tree canopies. The overestimation varied from year to year with differences in average cloud cover.

The mean erythemal exposure for people moving in the residential, open urban, and institutional land use classes during the 4 mid-day hours was 4.7 MED. The mean erythemal exposure in shaded areas was 2.2 MED. Exposures in the high-building-density residential land- use class were 27 to 29% higher than that in the low- to medium-density residential land use class.

Plans for future work include the addition of buildings to the relative irradiance models and verification of the modeling by above- and below-canopy radiation measurements.

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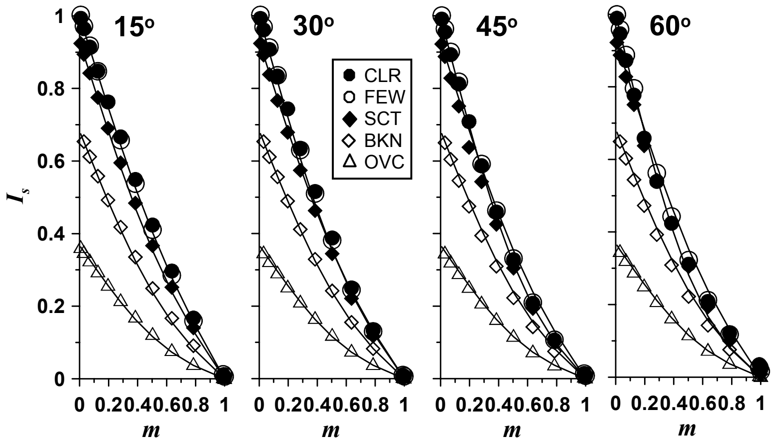

Figure 1. Mean spatial irradiance below canopy with clouds compared to above canopy irradiance with clear sky. Curves represent the modeled values based on Eq. [5].

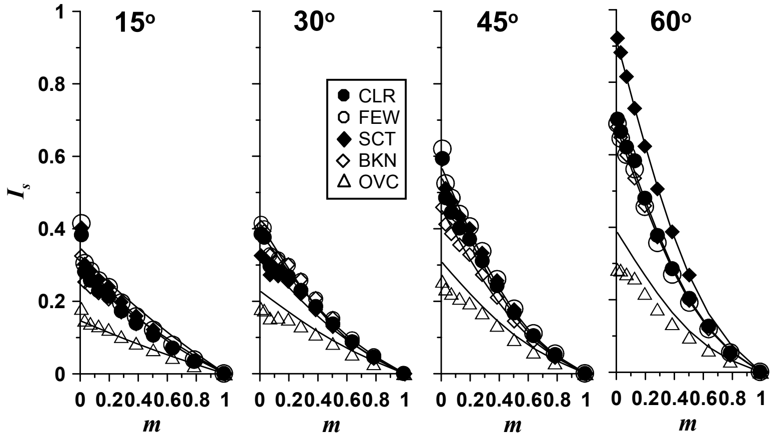

Figure 2. The effect of trees and clouds on below canopy irradiance in the shade. I_s is irradiance in the shade below canopy/irradiance above canopy with clear skies. Curves represent the modeled values based on Eq. [6]. The panel labels indicate solar zenith angles.

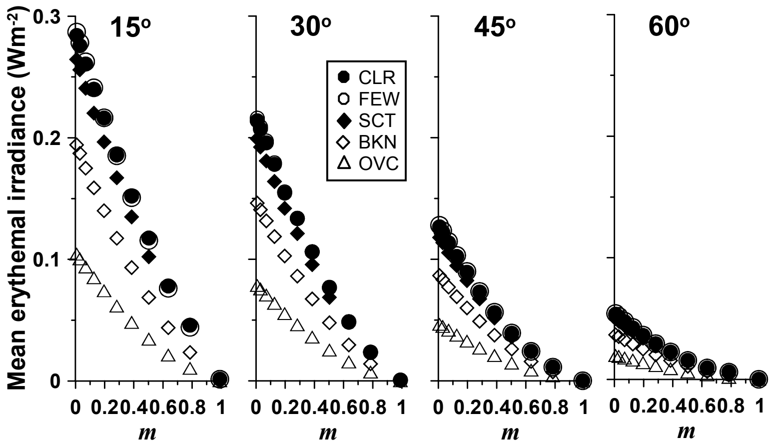

Figure 3. The spatial mean irradiance below canopy, averaged over both sun and shade locations. Panel labels indicate solar zenith angles. The assumed total column ozone was 280 DU.

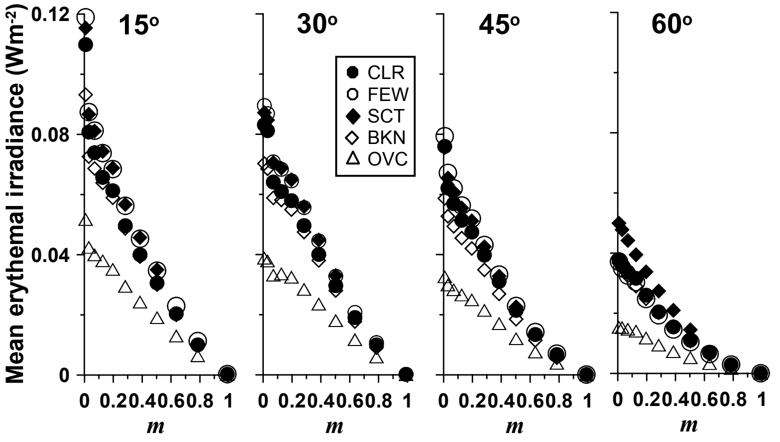

Figure 4. The spatial mean erythemal irradiances across the shaded regions of the array for varying cloud cover are indicated. The panel labels state the solar zenith angle for each set of irradiance predictions.