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Anisotropic Model for the Diffuse Biologically-Effective Irradiance of Solar UV-Radiation on Inclined Surfaces*

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With 1 Figure

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Summary

A model for biologically-effective ultraviolet radiation (UVR) of the sun is described, which allows the calculation of diffuse irradiance on inclined surfaces. A model is presented, for which isotropic scattered and reflected radiance are assumed. Using the horizon as a borderline between the upper and lower hemisphere, the scattering phenomena in the atmosphere for UVR are discussed. In contrast to models for other solar spectral ranges, the radiation field of UVR is close to isotropic. Only the horizon darkening by the long optical pathlengths was included in the model. This term was quantified by the UV albedo.

1. Introduction

For the development and application of models describing solar radiation the purpose of the model has to be considered. Most models are used for energetic considerations (Perez et al., 1986). These models cover the entire spectral range of solar radiation. For some photobiological applications however, only a narrow spectral range, described by corresponding spectral filter functions, is of interest. This study will explore the UVR. This spectral range is of particular biological importance as, on one hand, positive and/or desirable effects result (vitamin D; pigmentation) and, on the other hand, the development of skin cancer has been observed (van der Leun, 1984).

To investigate the interaction between UVR and the corresponding photobiological reactions, a quantification of the UVR is necessary (Bosnjakovic, 1988). The relevant receiving plane for this radiation is the body surface. Hence the necessity of models which describe the irradiance on inclined planes is evident (Dahlback and Moan, 1990; Diffey, 1988; Schauberger, 1990).

The goal of the model development is the description of the solar diffuse UV irradiance on inclined planes. The spectral restriction on biologically-effective UVR is considered with the development of the model. In contrast, known models (e.g., Perez et al., 1986, 1987) have been developed for the entire spectral range. As the extinction mechanism in the atmosphere depends greatly on the wavelength, independent developments for solar UVR are necessary.

2. Description of the Model

For arbitrarily oriented receiving planes the incoming radiation can be divided into three components:

(1) direct radiation DR: direct component which results from the radiation normal to the receiving surface, I_0, and the solar incidence angle, θ on the inclined plane;

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(2) diffuse radiation from the upper hemisphere DF_S: part of the radiation which comes from the half sphere (sky dome) above the horizon line on the receiving plane;

(3) reflected, diffuse radiation DF_R: is caused by ground reflection from direct and diffuse radiation (global UV-radiation).

In contrast to the diffuse components (2) and (3) the calculation of direct radiation DR is not discussed as it is an exclusively geometric problem. The quality of a model depends, above all, on an adequate description of the two diffuse radiation components.

2.1 *Isotropic Model*

2.1.1 Diffuse, Reflected Radiation

The diffuse, reflected component DF_R is described on the assumption of isotropic reflection by Eq. (1).

$$DF_R(\alpha) = DF(90°) f_R(\text{ISO}) \tag{1}$$

The change in irradiance, dependent on the inclination angle α, is calculated by multiplication of the irradiance on the horizontal $DF(90°)$ with the relative distribution function. The distribution function valid for the reflected radiation is given by

$$f_R(\text{ISO}) = \tfrac{1}{2} A(1 + \zeta)(1 - \sin\alpha) \tag{2}$$

where f_R is the relative distribution function for the reflected radiation, α angle of inclination (angle between the normal vector of the receiving plane and the horizontal), $\zeta = DR(90°)/DF(90°)$, the relationship between the direct radiation and the diffuse radiation on the horizontal, and A is the albedo of the UVR.

By using the factor ζ both the diffuse radiation from the upper hemisphere as well as the direct radiation DR are included in the reflected component DF_R.

2.1.2 Diffuse Radiation from the Upper Hemisphere

The diffuse part from the upper hemisphere is described analogously to Eq. (1) by the diffuse radiation on the horizontal $DF(90°)$ and a relative distribution function.

$$DF_S(\alpha) = DF(90°) f_S(\text{ISO}). \tag{3}$$

For the isotropic assumption, the relative distribution function is:

$$f_S(\text{ISO}) = \tfrac{1}{2}(1 + \sin\alpha). \tag{4}$$

The two diffuse components $DF_R(\alpha)$ and $DF_S(\alpha)$ can be described by summing up the two distribution functions (Eq. 5).

$$DF(\alpha) = DF(90°)[f_R(\text{ISO}) + f_S(\text{ISO})]. \tag{5}$$

2.1.3 Consideration of the Horizon Line

The Eqs. (2) and (4) for the relative distribution functions are based on the assumption that the horizon devides the upper hemisphere and the lower hemisphere into two solid angles of the same size. However, because of the actual shape of the horizon line is not an exact plane, this is not the case. The problem with this assumption is the dependence on the albedo A and the factor ζ (Eq. 2). By considering the horizon line, the solid angle is reduced for the diffuse sky radiation while the share of diffuse reflected radiation increases. To consider the shape of the horizon line, the mean elevation angle ϑ of the horizon line was calculated for parameterization. Thus the two relative distribution functions (Eqs. 2 and 4) are modified.

$$f_R(\text{ISO}, \vartheta) = \tfrac{1}{2} A(1 + \zeta)(1 - \sin(\alpha - \vartheta)) \tag{6}$$

$$f_S(\text{ISO}, \vartheta) = \tfrac{1}{2}(1 + \sin(\alpha + \vartheta)). \tag{7}$$

These two equations yield analogously, as in Eq. (5), the isotropic distribution function $f(\text{ISO}, \vartheta)$, the diffuse radiation $DF(\alpha)$, which are now modified by the horizon line.

2.2 *Anisotropic Model*

Model improvements are possible by the inclusion of the scattering which occurs in the atmosphere (Perez et al., 1986). By including scattering no constant value of radiance can be taken for the whole hemispheric radiance. The relative distribution function $f_S(\text{ISO})$ then is modified to:

$$f_S(\text{ANISO}) = f_S(\text{ISO}) + f_S(HD) + f_S(CS) \tag{8}$$

with two additional terms for the horizon darkening HD and circumsolar radiation CS.

2.2.1 Horizon Darkening

This effect is caused by the long optical pathlengths (Coulson, 1975), whereby an attenuation of the radiance is observed in the proximity of the horizon. At larger wavelengths a contrary effect is observed which is called horizon brightening. This is caused by the relative amount of scattered and absorbed radiation. Steven and Unsworth (1980) proposed a model for diffuse overcast sky radiation based on the following radiance distribution:

$$N(\gamma) = N(90°)\frac{1 + b\sin\gamma}{1 + b} \qquad (9)$$

where γ is the elevation angle between the horizon ($\gamma = 0$) and the observed element of radiance $N(\gamma)$, and b is a constant. The isotropic distribution assumes $b = 0$ and thus $N(\gamma) = N(90°)$. Integration of this function over the hemisphere of an arbitrarily oriented plane element yields the diffuse irradiance from the upper hemisphere DF_S. The parameterization of the anisotropy through the factor b expands the relative distribution function (Eq. 4) by an additional term:

$$f_S(HD) = \frac{2b}{\pi(3 + 2b)}(\cos\alpha + \alpha\sin\alpha - \pi/2) \qquad (10)$$

where α is in radians.

For the model the determination of the factor b for the spectral range of the biologically-effective UVR is necessary. In Eq. (10) the first term is a broken function in b. As a result of discontinuity in the zero point of the denominator this function is replaced by a factor H. The second term of this equation is replaced by an essentially simpler function with a nearly identical functional shape. Equation 10 then takes the form:

$$f_S(HD) = H\sin^2\alpha. \qquad (11)$$

2.2.2 Circumsolar Radiation

This component of diffuse radiation from a narrow region close to the sun is caused by forward scattering. As the solid angle is very limited, this component can be described analogously to direct radiation DR over the solar incidence angle θ on the inclined plane. The circumsolar component $C(\theta)$ is described by

$$C(\theta) = C_0\cos\theta \qquad (12)$$

where C_0 is the irradiance of the circumsolar radiation for $\theta = 0$, analogous to the normal radiation I_0. For radiation on a horizontal plane the incidence angle θ is determined by the elevation of the sun h, so that $C_0 = C/\sin h$. So Eq. (13) is a term of the anisotropic distribution function f_S(ANISO) (Eq. 8) by:

$$f_S(CS) = C\left[\frac{\cos\theta}{\sin h} - \tfrac{1}{2}(1 + \sin\alpha)\right]. \qquad (13)$$

3. Material and Method

The technique measured the radiation intensity at 26 differently aligned receiving surfaces. The 26 measuring points were arranged in a horizontally coordinated system, which was directed towards geographic north. The position of each measuring point was determined by its azimuth β, which is measured clockwise starting at geographic north, and its angle of inclination α. The latter is measured positively from the horizontal plane towards the zenith and negatively towards the nadir. The following measuring points were chosen: horizontal against the zenith (angle of inclination 90°); 8 points (45° horizontally apart from each other) at an angle of inclination of +45°; 8 points at an angle of inclination of 0° (receiving surface normal to the horizontal plane); 8 points at an angle of inclination of −45°; and the nadir (horizontal receiving surface), pointed towards the ground at −90°. For the horizontally oriented measuring point (zenith) both the global radiation as well as the diffuse radiation were measured. This was done by shadowing the direct component of the global radiation, so the difference between the two yields the direct radiation DR (90°).

The UV sensor was attached to a tripod which allowed flexibility of movement. A compass was used to determine geographic north and the horizontal was verified with a clinometer. The accuracy of the angle adjustment was approximately ±3°. Measurements were made with a Berger sunburn meter (models 5D and 3D, Solar Light Co.). Its spectral sensitivity corresponds approximately with the erythema action spectrum proposed by Parrish et al. (1982). The measuring device indicates the measurements in Minimal Erythema Doses per hour (MED/h).

The sensor has an adequate cosine-weighted response; this was tested at an optical bench using a UV point source. As all measurements were done in outdoor conditions, the sensor and its associated radiometer were both tested for response to any influence of temperature. Measurements carried out in a climatec chamber with a temperature range from 0 °C to 25 °C did not produce any changes in sensitivity.

The measurements of 800 series were taken at 33 different measuring sites. Date and time of the measurements, a description of the location and the prevailing conditions were recorded. The conditions were determined by a combination of ground cover, cloud cover (octals) and the cloud intensity (3 grades).

For the horizontally oriented receiving plane (against the zenith) the diffuse radiation $DF(90°)$ can be calculated from the difference between global radiation and direct radiation $DR(90°)$. From this the normal radiation I_0 is calculated using the solar elevation angle h. To be able to calculate the direct and diffuse component for all measuring points, the solar incidence angle θ of direct radiation on the respective receiving plane is necessary; for inclination angles $\theta \geqslant 90°$ the direct component $DR = 0$.

The inclination angle θ, the angle between the direct radiation and the normal vector of the receiving plane, is determined on one hand from the sun elevation angle h and the azimuth of the sun Az, and on the other hand from the inclination angle α and the azimuth β of the receiving plane. The two coordinates of the sun, h, and Az, are calculated from the recorded date and clock time (local time) of each measurement as well as the geographical coordinates of the measuring point. For this one of several well-known calculations can be used (e.g., Björn, 1989).

For each measuring point the course of the horizon line through the measurement of the elevation angle of the horizon line in an azimuth distance of 30° was documented.

4. Results

For each value of the data set the residual between the respective model, represented by the relative distribution function f, and the relative diffuse irradiance $DF(\alpha)/DF(90°)$ were calculated. This was used to calculate the parameters of the model and to evaluate the presented models.

To change from the isotropic to the anisotropic model, the determination of the respective parameters of the relative distribution functions is necessary. The parameters C and H of the distribution functions $f_S(CS)$ and $f_S(HD)$ are calculated using a two-dimensional regression analysis for the residual of the isotropic model f_S(ISO). The regression plane goes through the origin because the constant of the regression was set to zero. In Table 1 the results of the analysis are summarized. They show that inclusion of the circumsolar component provides no essential improvement. For further investigations, the factor C is set to 0. Thereby, it is possible to dismiss azimuthal dependence of the model and the parameters of geometry are reduced to the inclination angle α. Thereby an average over the azimuth (2π) for all measuring points with equal inclination angle provides a useful reduction of the dataset.

Table 1. *Result of the Two-Dimensional Regression Analysis of the Residual $R_S(ISO)$ for the Isotropic Model f_S of Solar Radiation from the Upper Hemisphere for the Determination the Factors C and H of the Anisotropic Model.* $R_S(ISO) = f_S(ISO) - [DF_S(\alpha)/DF(90°)]$

Regression coefficient r	0.297
Degree of freedom	8190
C (±SD)	−0.0004±0.0012
H (±SD)	0.1519±0.0017

Table 2. *Coefficients of the Linear Function $H = \alpha A + b$, Calculated by a Regression Analysis from the Residual of the Models $f_S(ISO)$ and $f_S(ANISO, \vartheta)$* (part of the diffuse radiation from the upper hemisphere) ($N = 1122$; H parameter of $f_S(HD)$; A UV albedo)

	$\alpha + SD$	$b + SD$	$\|r\|$
H (ISO)	−0.3853±0.0191	0.2029±0.0042	0.516
H (ANISO, ϑ)	−0.5244±0.0234	0.1144±0.0051	0.557

Perez et al. (1986, 1987) determined the factors of their models through linear combination of parameters which describe the location and the prevailing conditions (e.g., solar elevation angle, insolation conditions by the horizontal diffuse irradiance and cloud cover). For the biologically-effective UVR, as found for the whole spectrum, no connections could be determined for these parameters.

The influence of albedo is different: Steven and Unsworth (1980) point to the influence of albedo on the horizon darkening component. By replacing the function in b (Eq. 10) by the factor H, the dependency of H on the albedo (A) was examined. Table 2 shows the results of the linear regression

Table 3. *Mean Value and Root Mean Square of the Residual for All Models for the Relative Diffuse Irradiance Calculated for Three Inclination Angles 45°, 0° and −45° of the Geometry as Well as for All Measuring Points Together*

Model	Inclination angle α			
	−45°	0°	45°	All
f(ISO)	0.0656 ± 0.0594	0.1164 ± 0.0805	0.0973 ± 0.0743	0.0931 ± 0.0749
f(ISO, ϑ)	0.0099 ± 0.0847	0.0313 ± 0.1087	0.0327 ± 0.0894	0.0246 ± 0.0953
f(ANISO)	-0.0081 ± 0.0390	-0.0312 ± 0.0638	0.0236 ± 0.0711	-0.0052 ± 0.0636
f(ANISO, ϑ)	-0.0094 ± 0.0600	-0.0072 ± 0.0860	0.0135 ± 0.0834	0.0010 ± 0.0780

analysis. The factors for a linear regression function were selected so that the mean value of the residual for all inclination angles of the dataset for the distribution functions f_S(ANISO) and f_S(ANISO, ϑ) was equal to zero. The models were compared with each other. The assessment used the mean of the residual as well as the root mean square of the residual for the three inclination angles 45°, 0°, and −45° of the geometry as well as for all measuring points together. In Table 3 the results of the model comparison are summarized.

5. Discussion

Although many models exist describing solar irradiance on inclined planes, a separate development for UVR is worthwhile. This necessary because of the strong dependence of scattering on wavelength (up to λ^{-4}). The biologically-effective spectral range, marked here as UVR, is determined by the spectral sensitivity of the erythema. Hence the model is suited for photobiological applications in this spectral range. In contrast to most models the role of diffuse radiation is explained not only by the upper hemisphere but also by the reflected component of ground cover. Thus not only the diffuse radiation on the horizontal but also the albedo and the relationship ζ between the direct and diffuse radiation on the horizontal are used for the calculation. It should be considered, however, that the albedo relates to the biologically active UVR for erythema. The albedo in the UV area has already been investigated (Ambach and Eisner, 1986; Blumthaler and Ambach, 1988; Schauberger, 1990), so here only two important applications should be mentioned: snow-free ground cover with an albedo of below 0.1 and values between 0.3 and 1.0 for snow-covered ground.

The dataset of this experiment covers 26 differently oriented receiving planes in which the UV irradiance was measured. Because of overlapping of these 26 receiving planes, the measuring geometry has a high redundancy. Conclusions about the anisotropic behavior of the radiance distribution over the upper hemisphere are therefore justified. The measuring data fitted the models which were developed for the UVR.

For the isotropic model (ISO) it is assumed that both the radiance distribution of the sky as well as the reflection of the ground cover is isotropic. The first model improvement places the inclusion of the horizon as an actual borderline between the upper hemisphere and that part of the sphere from where the reflected part of the diffuse radiation originates (Anfield, 1986). The possible extent of the reduction of the view factor of the sky by obstacles above the horizon was shown by Watson and Johnson (1988). For the assumption that the horizon is the borderline between the sky and the ground cover, the sky is 50% of the whole sphere. It should be noted that in urban areas the sky is often reduced to 20% or less. This demonstrates that the horizon line and not the horizon (Perez et al., 1986, 1987; Steven and Unsworth, 1980) needs to be used for describing the radiation geometry.

A strong difference between the radiance distribution of UVR compared with the entire spectrum is caused by the strong wave-length dependence of extinction. For the whole spectrum, the circumsolar radiation is largely responsible for the anisotropic behavior (Perez et al., 1987). Bird and Riordan (1986) included exclusively circumsolar radiation in their model. This factor is largely reduced in the UV area (Table 1).

The effect caused by attenuation of radiation on the long optical pathlengths in the proximity of the horizon shows an interesting characteristic

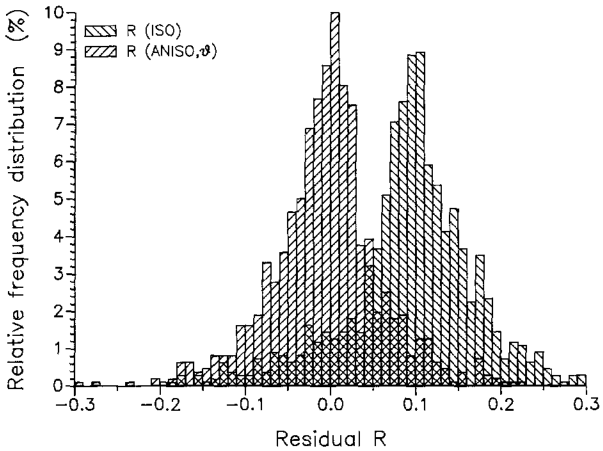

Fig. 1. Relative frequency distribution of the residual R of the isotropic model f(ISO) and the anisotropic model f(ANISO, ϑ). $R(\text{ISO}) = f(\text{ISO}) - [DF(\alpha)/DF(90°)]$ and $R(\text{ANISO}, \vartheta) = f(\text{ANISO}, \vartheta) - [DF(\alpha)/DF(90°)]$

for UVR. From the spectral radiance distribution for clear sky calculated by Nagel et al. (1978), it can be shown that for wavelengths over 340 nm there is brightening, while for smaller wavelengths there is a decrease of radiance. Furthermore, cloud cover plays an important role in the entire spectrum. For a clear sky, horizon brightening of up to 40% of the zenith value is observed (Steven and Unsworth, 1979; Perez et al., 1987). The models of Steven and Unsworth (1980) and Perez et al. (1987) show that an overcast sky reduces the zenith value by about 10%, whereas Dirmhirn (1964) observed a reduction by horizontal darkening up to 70%. For the UVR, the horizon darkening has a weak influence on the radiance distribution. Furthermore, no dependence on cloud cover was found. Compared with the entire spectrum UVR can be marked as closely isotropic. This is shown also by Fig. 1, where the relative frequency distributions of the residual are presented for all angles of inclination for both the isotropic model f(ISO) and the anisotropic model f(ANISO, ϑ), taking the horizon line into consideration. The two distributions show that even on the assumption of an isotropic radiance distribution of the sky f(ISO) the resulting error is small.

The description of the horizon darkening using the integration of the anisotropic radiance distribution (Steven and Unsworth, 1980) facilitates the interpretation of the factor H. Perez et al. (1987) interpreted negative coefficients of this term strictly by a better fit of the data; here this is not a problem. The factor H in the anisotropic term $f_S(HD)$ gives the deviation of the radiance of the reference quantity N (90°) at the horizon (Eq. 9).

6. Conclusion

The strong spectral dependence shows that the unchecked use of a model, valid for the entire spectral range, is not acceptable. This can also be said for the application of such models to spectral data as proposed by Bird and Riordan (1986). The slight influence of anisotropic effects by horizontal darkening for UVR allows a very simple model structure which facilitates the application of the model.

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