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Solar energy input to plant surfaces: I. Modeling of spectral power distribution with the computing program ECOSOL

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Abstract

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A radiation model, called ECOSOL, to calculate solar energy input to plant surfaces is presented. The diurnal variation of direct and diffuse radiation and their spectral power distribution for clear sky conditions can be modeled for any slope angle of the receiving surface and any geographical site. In combination with measured spectral optical properties of plants the absorbed radiation can be estimated.

The calculation of atmospheric transmittance is based on the computer code LOWTRAN 3, 3 B and 4. For modelling the scattered sky radiation a relatively simple model was adopted to take into account the anisotropical distribution of clear sky radiance. When reflected radiation by the fore ground is modeled, its measured reflection properties can be applied. Several comparisons with pyranometric and spectroradiometric data are given to show the reliability and accuracy of the calculated data.

Key words: Modeling (solar radiation), PAR, sky radiation, solar radiation, spectrum (solar radiation).

Introduction

The detailed knowledge of the diurnal variation of global irradiance and its spectral power distribution is of great importance for many fields of research. Energy budget and radiation studies based on spectral power distribution of solar radiation and spectral optical properties of plants (Gates and Papian 1971, Gates 1980) and their application in field investigations have an increasing importance in studies of plant ecophysiology (Schulze et al. 1980, Eller and Grobbelaar 1982, Eller et al. 1983). Recent studies (Lee and Graham 1986, Ehleringer and Werk 1986, Terashima and Takenaka 1986, Adams III et al. 1988) demonstrated that knowledge of natural lighting conditions and/or their spectral distributions is also important for anatomical and physiological investigations concerning photosynthesis and plant production.

When dealing with the estimation of parameters which are dependent in a non-linear way on the incoming radiation, as e.g. the photosynthetic rate of most plants (Björkman 1981), the leaf temperature (Gates 1980) or the stomatal conductance (Burrows and Milthorpe 1976, Wong et al. 1978), the actual value of global irradiance on the surface under investigation is indispensable. It is a desirable aim in ecophysiological research to measure power of radiation and the spectral distribution incident on a plant surface. However this can only be achieved for flat surfaces and provided there is enough space for the radiation sensor. The pyranometer is a commonly used instrument for determining the daily course of the global radiation incident on a flat surface, whether horizontal or tilted. However difficulties arise if the global energy input has to be determined for folded, bent or twisted leaves or leaves with even more complex shapes (e.g. many succulent plants). It is only rarely feasible to perform simultaneous measurements with a greater number of sensors oriented to describe the exposition of different plant surfaces. Moreover distinction must be made between direct and diffuse radiation in case of shading over a considerable part of the day. This may be caused by self or mutual shading as in a rosette, in trees or canopies or by other obstructions in the foreground.

Modeling of the spatial and spectral distribution of direct and diffuse radiation impinging on a particular surface element of a geometrical complex plant surface seems to be a way to replace multiple simultaneous measurements and to solve the mentioned problem. Depending on the complexity and aim of the investigations the modeling can be done in different manners. Much work has been done to model the lighting conditions and productivity of canopies by theoretical considerations about light penetration, leaf area, leaf inclination and azimuthal distributions, gap frequencies or penumbral influences (for a review see e.g. Ross 1981). In investigations where irradiation values are needed, the irradiance is usually determined as total global radiation (Gates 1980) or by separating the global and diffuse radiation into the photosynthetically active radiation (PAR) between 400 and 700 nm (Gueymard 1989, Garcia de Cortazar et al. 1985) and the infrared radiation (IR) between 700 and 3000 nm (Varlet-Grancher 1975, Thorpe et al. 1978).

In this paper a computing program ECOSOL is presented for modeling the diurnal variation of direct and diffuse radiation and their spectral power distributions inciding on a given surface of any orientation for clear sky conditions. It is designed for applications in connection with ecophysiological field research, where the actual lighting conditions of individual leaves, plant parts or a limited arrangement of leaves as for a rosette are needed. It was not the primary aim to use this program for investigations in complex or dense canopies. However further extension of the program for such research would be feasible.

ECOSOL serves for example for a proper relation of measured ecophysiological parameters as photosynthesis, leaf temperatures or transpiration with respect to incident or absorbed energy or quantum flux. It can also be used to study the effects of different light climatic conditions on the mentioned parameters or energy balances. The diffuse radiation in particular can show large variations in spectral composition for different orientations of the receiving surface, depending on the amount of radiation reflected or transmitted by the environment. Together with the spectral properties of soils, rocks or neighbouring leaves changes of the spectral power distribution of the reflected or transmitted component of the incident radiation can be modeled.

Its application is considered in connection with an appropriate number of measurements of actual global, diffuse radiation and/or spectral power distributions, as the equipment of an ecophysiologist is normely supplied with a pyranometer or a quantum sensor. These measurements, for example the diurnal course of horizontal global radiation, serve for an estimation of the actual turbidity and for choosing the appropriate meteorological range for the calculation procedure, as described in "Methodology". In combination with measured spectral absorption properties of the leaf or tissue under investigation the absorbed energy or quantum flux can be calculated and e.g. effects of their changing during leaf development (Eller 1984, Ehleringer and Werk 1986, Tanner and Eller 1986 a) or of special features of the epidermal structures (Eller 1985, Tanner and Eller 1986 b) can be studied.

To solve the problem of complex surface shapes an approximation can be made either by a geometrical solid with even surfaces e.g. pyramid, cylinder etc. in the case of succulent plants, or for normal thin leaves by an arrangement of triangles which are defined by the spatial coordinates of their angles (Flach 1986).

In this paper the methodology of calculation is presented together with several comparisons of measured and calculated data. The application of the program in connection with ecophysiological research as outlined above is published elsewhere (Eller and Flach 1990, Flach and Eller 1991).

Methodology

Considering the ecophysiological applications mentioned in the preceding chapter a calculation procedure was sought which fulfills the following requirements:

1. Modeling of direct and diffuse radiation and thereby global radiation and their spectral power distribution on an arbitrarily inclined plane.
2. Measured reflection, transmission and/or absorption properties can be taken into account.
3. The computing program should be limited to clear and cloudless weather conditions, i.e. observer visibilities V_{obs} greater than 11.5 km or meteorological ranges V greater than 15 km with $V \approx (1.3 \pm 0.3) \cdot V_{obs}$ (Kneizys et al. 1980).
4. The modeling of actual irradiation values is based on measured pyranometer and/or quantum sensor data and eventually on some spectroradiometer data depending on the equipment and the aim of research. The measurements serve for the estimation of the actual turbidity conditions. A pyranometer or a quantum sensor is normally part of the ecophysiological equipment for field research. The use of the programm should *not* forcingly depend on the determination of spectral meteorological parameters such as turbidity, aerosol composition, total precipitable water vapour or total amount of ozone. The collection of such data normally exceeds the equipment of a plant ecologist.
5. As the irradiation calculations serve also as a basis for further calculations, e.g. in combination with measured ecophysiological parameters, the calculation procedure should give as accurate results as possible, but should not be too complex and time consuming as e.g. rigorous transfer codes for diffuse spectral irradiances.

The basic assumptions and data for the calculation procedure for direct solar radiation and diffuse radiation are summarized below. The program is based on the computing codes LOWTRAN 3, 3 b and 4 (Selby and McClatchey 1975, Selby et al. 1976, Selby et al. 1978) for calculating the spectral transmission of a given atmospheric path. A detailed description of the procedures for the calculation by ECOSOL is given in Flach (1986) together with a listing of the program in PL1. (Listing available on request.) The extraterrestrial spectrum after Neckel and Labs (1984) forms the basis of the calculation.

The spectrum for the ultraviolet radiation (UV) was extended below 330 nm down to 220 nm by values of Broadfoot (1972) and Arvesen et al. (1969) and in the infrared (IR) up to 3000 nm by those of Arvesen et al. (1969) and Labs and Neckel (1970).

The position of the sun for a given time and geographical place is calculated by means of the appropriate equation from spherical trigonometry. The annual variation of the sun-earth distance, the solar declination and the equation of time were taken from the "Astronomical Almanac for the Year 1981" under consideration of leap-years.

The calculation of the transmission values for each wavelength follows the procedure of LOWTRAN 3 and 3 b (Selby and McClatchey 1975, Selby et al. 1976) with only some minor adaptations. This concerns the added calculation of refractional correction, the refractive index and the Rayleigh volume scattering coefficient which are calculated after Edlén (1966) and Penndorf (1957), respectively. Atmosphere models of 34 layers with height profiles for temperature, pressure, water vapour and ozone content and aerosol concentrations form the basis of the calculations. Depending on the sea-level meteorological range, which serves as input data, the aerosol concentrations of the first five levels between a height of 0 and 5 km can be varied. The atmosphere and also aerosol models can be chosen as input data sets. For the height profiles of the atmosphere the midlatitude summer (MIDSUM), midlatitude winter (MIDWIN), subarctic summer (SARSUM) and tropical (TROPIC) model adopted after Selby and McClatchey (1975) are available and for the wavelength dependent extinction and scattering properties of aerosol the rural (RURAL), urban (URBAN) and tropospheric (TROPOS) model after Selby et al. (1976). For warmer and drier conditions a modified midlatitude summer model (MODMISU) was established with adjusted values for the temperature and water vapour content in the first five atmospheric levels between 0 and 5 km (Flach 1986).

With these methods and assumptions the basis for the modeling of direct solar radiation is provided. For the calculation of diffuse radiation a special procedure was created. It is well known, that even an approximately rigorous calculation of the diffuse radiation is extremely laborious. In order to fulfill nevertheless point 5) of the requirements, the adopted solution was guided by two ideas:

1. Calculation of the scattered part of the diffuse radiation from one distinct point of the celestial hemisphere to a receiving surface according to the proposition by Smith et al. (1979) for the modification of the LOWTRAN 4 version to include first order solar scattering.
2. The option of this distinct point is in such a way, that its radiance is representative for the part of the celestial hemisphere which is viewed by the surface under investigation, i.e. the hemisphere is assumed to radiate isotropically with this radiance.

The equation given by Smith et al. (1979) for the fraction $H_{P,i}(\lambda, \gamma_i)$ of light scattered along the line of sight to the observer (with zenith angle z_N) by the i-th layer of the model atmosphere is

$$H_{P,i}(\lambda, \gamma_i) = I_S(\lambda) \cdot t' \cdot \sigma \cdot t \cdot P(\cos \gamma_i) \cdot N_i \tag{1}$$

where $I_S(\lambda)$ is the extraterrestrial irradiance [W/cm^2/nm], t′ the transmittance from space to the i-th layer at zenith angle z_S, σ the scattering cross section [cm^2], t the transmittance from the i-th layer to the observer at zenith angle z_N, $P(\cos \gamma_i)$ the scattering phase function for scattering angle γ_i [ster^{-1}] and N_i the column density of scatterers along a slant path to the observer through the i-th layer [cm^{-2}]. This equation shows that the task to find a representative point is twofolded: on one hand it needs an appropriate scattering angle or rather an appropriate value of the scattering phase function for the aerosol and molecular scattering and on the other hand the appropriate atmospheric path for the transmission calculation by the LOWTRAN program.

For scattering phase function the known Rayleigh function for molecular scattering and the 1 µm function for the rural aerosol model given by Smith et al. (1979) were used. The search for the appropriate values for a given exposition of the receiving surface and a given zenith angle of the sun was guided by two facts: (1) The values are dependent on the angular distance between the direction to the sun and the normal to the receiving surface. (2) A surface, which is isotropically irradiated by a hemisphere around it, receives its major contribution from the ring at a 45° angular distance from its vertical. This is obvious when taking the integral of the isotropic component $H_P(\lambda)$ over the whole hemisphere:

$$H(\lambda) = H_P(\lambda) \int \cos \vartheta \, d\omega = H_P(\lambda) \int_{\varphi} \int_{\vartheta} \cos \vartheta \sin \vartheta \, d\vartheta \, d\varphi \tag{2}$$

where $H_P(\lambda)$ is the specific intensity of the diffuse sky radiation [$W\,m^{-2}\,nm^{-1}\,ster^{-1}$], $d\omega = \sin \vartheta \, d\vartheta \, d\varphi$ the elementary cone of solid angle, ϑ the angle between the direction of $d\omega$ and the vertical and φ the azimuth of $d\omega$.

By expressing the looked-for relationship as a mathematical function it is easy to handle in the computing algorithm. Comparison of modeled sky radiation data with reported literature data (Gates 1980, Ross 1975, Kondratyev 1969 and own measurements (unpubl.)) led to the following functional relations for the aerosol and molecular phase functions P_{aer} and P_{mol} from the angle γ, i.e. the angle between the direction to the sun and the normal to the receiving surface:

$$P_{aer}(\gamma) = \begin{cases} \mathrm{tg}^{-1}(5.25-\gamma/20.0)/600 & 0° < \gamma \leq 80° \\ 0.0856-0.0556 \cdot (\gamma-80.0)/45.0 & 80° < \gamma \leq 125° \\ 0.030 & 125° < \gamma \leq 180° \end{cases} \tag{3}$$

$$P_{mol}(\gamma) = \begin{cases} 0.0950 & 0° < \gamma \leq 25° \\ 0.0950-0.0254 \cdot (\gamma-25.0)/55.0 & 25° < \gamma \leq 80° \\ 0.0812 & 80° < \gamma \leq 180° \end{cases} \tag{4}$$

As the calculation according to Smith et al. (1979) concerns only first order solar scattering and the single scattering is only a useful approximation in the wavelength region 1–5 µm, a wavelength dependent correction function was created for wavelength shorter than 1 µm. In considering the restriction that the calculation program should hold only for clear sky conditions, the investigations of Deirmendjian and Sekera (1954) for a Rayleigh atmosphere were used. Their ratios $H(\lambda)^1/H(\lambda)$ of sky radiation from primary scattering to that one from all orders of scattering $H(\lambda)$ were approximated by:

$$H(\lambda)^1/H(\lambda) = (a \cdot (0.01 \cdot \lambda)^b + 1.0)^{-1} \tag{5}$$

with a correlation coefficient of 0.997, where $a = 121.59$, $b = -3.764$ and λ the wavelength in nm. This equation holds for a solar zenith angle of 53.1°. To take into consideration the variations with the solar zenith angle z_S the exponent b of equation (1) can be written in the form

$$b = -4.0 + 0.4 \cdot (z_S/90). \tag{6}$$

With this expression a good fit is obtained to the values given by Deirmenjian and Sekera (1954) for solar zenith angles from 0° to 84.3°.

For adopting the appropriate pathway for calculating the transmission of the scattered radiation it was assumed a pathway of 45° zenith distance for a horizontal surface. The zenith angle of the pathway z_P grows linearly with tilting of the surface up to 81° for 180° inclination:

$$z_P = z_N \cdot 0.2 + 45.0 \tag{7}$$

where z_N is the zenith angle of the normal to the receiving surface.

To account for the increasing brightness of the sky toward the horizon in the vicinity of the sun and its azimuthal variation relative to the sun's position, the calculated sky radiation is multiplied by the function:

$$EW = 0.3 \cdot \cos(a_S - a_N) \cdot z_N/90 + 1.0 \tag{8}$$

where a_S is the azimuth of the sun and a_N the azimuth of the normal to the receiving surface. The factor EW and its azimuthal variation was determined by comparing calculated values of scattered radiation on a vertical surface for solar zenith angles of 35° and 55° with the corresponding values given by Steven and Unsworth (1979).

Integration of equation (4) over the appropriate ranges of ϑ and φ for the viewed part of the celestial hemisphere by the considered surface gives for isotropic radiation the relation

$$H(\lambda) = H_P(\lambda) \cdot \pi/2 \cdot (1 + \cos z_N). \tag{9}$$

The reflected radiation is also assumed to be isotropically distributed. It is calculated from the direct $D(\lambda)$ and the sky radiation $H(\lambda)$ on a horizontal exposed surface, taking into account the reflection properties $r(\lambda)$ of the environment. Its component $R_P(\lambda)[\text{ster}^{-1}]$ is given by

$$R_P(\lambda) = r(\lambda) \cdot (D(\lambda) \cdot 0.75 + H(\lambda)). \tag{10}$$

The arbitrary correction factor 0.75 for the direct component takes into account that rarely the whole environment reflects direct solar radiation. It can be altered in the case of special conditions. The integration over the viewed part of the hemisphere represented by the environment is then the difference between the area of the whole hemisphere and the part taken up by the sky as expressed in equation (9):

$$R(\lambda) = R_P(\lambda) \cdot \pi/2 \cdot (1 - \cos z_N). \tag{11}$$

For general use two different input data sets of spectral reflection properties are available as average values for different types of soils and rocks (ALLSOIL) or vegetation (ALLVEG) (after Wolfe and Zissis 1978). To allow for obstacles in the foreground that block a part of sky radiation or an elevation of the skyline, the reflected radiation is proportionally increased and the sky radiation reduced.

The program ECOSOL can be run in three different modes for any given inclination of the receiving surface:

1. Calculation of a spectral data set and wavelength integrated radiation data for a given solar zenith angle.
2. Calculation of a spectral data set and wavelength integrated radiation data for a given time with specification of the geographical site.
3. Calculation of wavelength and time integrated radiation data for a distinct time period between sunrise and sunset with specification of the time interval for the calculation steps and the geographical site.

Each mode gives the values of direct, diffuse and global radiation separately. Additional data of transmitted or absorbed radiation are calculated when the corresponding optical properties are specified. The wavelength integration is done separately for each kind of radiation (direct, diffuse, global, transmitted or absorbed) in the ultraviolet 300–400 nm (UV), the visible 400–750 m (VIS), the infrared 750–1350 nm (IR1), the infrared 1350–3000 nm (IR2) and the total range 300–3000 nm. Likewise, the quantum flux in the photosynthetically active range 400–700 nm (PAR) is calculated.

Results and comparisons between measured and calculated radiation data

In order to verify the modeling of radiation data by ECOSOL and to give some measure of its accuracy, several clear sky measurements were performed with recently calibrated pyranometers (Kipp and Zonen, Delft, NL) and spectroradiometers (LICOR inc. and ISCO, Lincoln, Nebraska, USA). Some comparisons with data from other authors are also given.

On February 5, 1987 near Nieuwoudtville (Cp., Rep. South Africa, 19°03′ east longitude, 31°25′ south latitude, 750 m altitude) the daily course of global and diffuse irradiation on a horizontally exposed surface was recorded by a pyranometer. For the registration of the diffuse radiation an occultation disk was used with a 6° field-of-view. The horizon was free of any obstruction. This measurements were made in connection with ecophysiological field research on spectral optical properties of leaves.

The day showed very clear and dry conditions with a visibility greater than 50 km. For the calculation procedure the tropospheric aerosol model TROPIC was chosen and the modified midlatitude summer model MODMISU for the height profiles of the atmosphere.

The measured and calculated data as a function of the solar zenith angle are compared in Fig. 1. The percentage difference lies with 3% for the global and within 10% for the diffuse radiation. The uncertainty of the measured global irradiance amounts to 2%–3%. The measured values of the diffuse radiation are assumed to be about 8–10% too low because of shading of circumsolar radiation by the occultation disk (Gueymard 1986).

On February 10, 1987 spectral distributions of global and diffuse radiation were measured for a horizontal surface at the same site. The global radiation was recorded simultaneously by a pyranometer. The weather was dry and clear as on February 5. The same aerosol and atmosphere model were used for the modeling of the radiation data. By adopting a sea-level meteorological range of 100 km a likewise good fit could be obtained to the pyranometer data.

Fig. 2 shows the measured and calculated global and diffuse spectra for 14h04/14h09 and 17h15/17h19 local standard time, corresponding to solar zenith angle of 22.6° and 60.6°, respectively. Below 350 nm and above 1000 nm the uncertainty of the spectroradiometer data increases strongly. The range of deviation of the true cosine response is specified by the manufacturer to ±8% up to 60° angle of incidence. The measured and modeled global spectra show differences up to 10% between 350 and 1000 nm. The differences between the diffuse spectra are larger, up to 30% for 14h09 and 25% for 17h19 between 300 and 700 nm, with measured values consistently below modeled ones. About 10% may be due to the same effect of the occultation disk as for February 5 and another part of the discrepancy is expected to arise from incomplete cosine response for angles of incidence greater than 60°. When the spectra are normalized at 500 nm they do not differ by more than 15% between 350 and 700 nm.

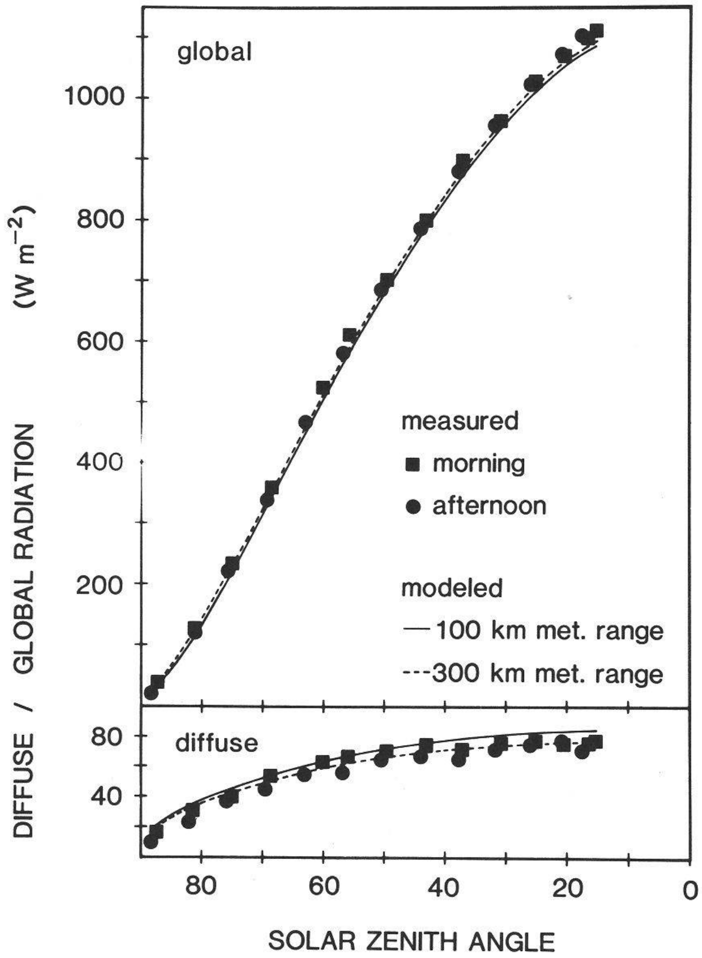

Fig. 1. Measured and calculated horizontal global and diffuse radiation as a function of solar zenith distance on February 5, 1987 near Nieuwoudtville (Cp., Rep. South Africa). The calculation was performed for 100 km and 300 km sea-level meteorological range.

As the infrared parts of the calculated spectra, i.e. wavelengths larger than 1000 nm, could not be properly verified by the available spectroradiometers, a global irradiation spectrum measured by Bird et al. (1983) was modeled. The data were collected on August 5, 1981 at 15h09 MST at Golden, Colorado (USA). The computation was done by means of MIDSUM for the atmospheric height profiles and RURAL for the aerosol properties. A sealevel meteorological range of 23 km was adopted. The comparison of the two spectra is given in Fig. 3.

During the data recording by Bird et al. (1983) the amount of precipitable water (2.25 cm) was obviously very high compared to the content of the model atmosphere (0.83 cm). The calculated absorption bands of water vapour are therefore not deep enough. The oxygen band at 690 nm do not appear in the calculated spectra of Figs. 2 and 3, nor an unknown absorber at about 1200 nm. The later one was already mentioned by Bird et al. (1983). Outside these absorption bands the modeled spectrum closely fits the measured one and it can be concluded that the calculation gives reliable results.

Between April 15, and July 7, 1982 pyranometer measurements were made on several clear days for variously inclined planes. The pyranometer was mounted on a coordinate table to adjust the zenith and azimuth angle of the receiving surface to the desired

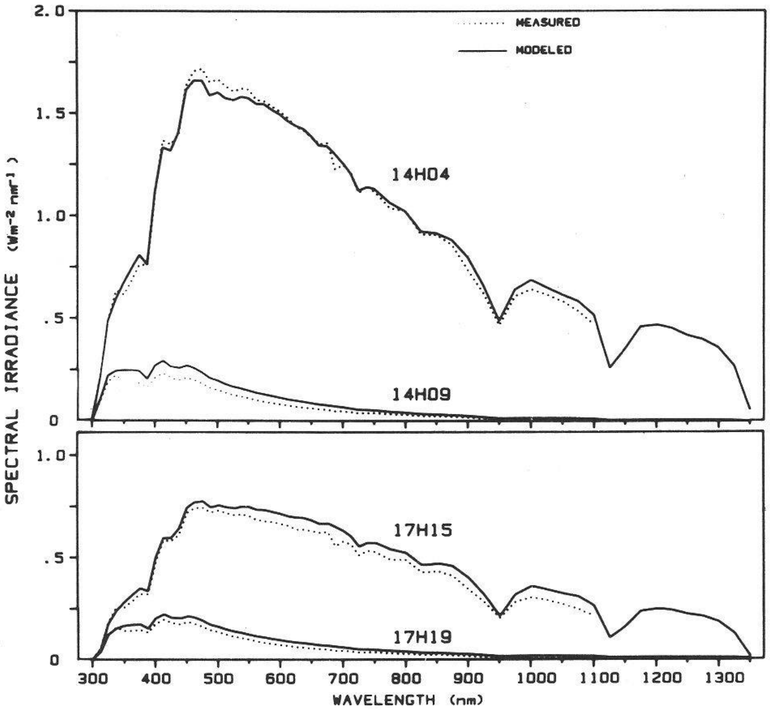

Fig. 2. Measured and calculated horizontal global (14h04, 17h15) and diffuse (14h09, 17h19) spectral irradiances on February 10, 1987 near Nieuwoudtville (Cp., Rep. South Africa). Time: local standard time.

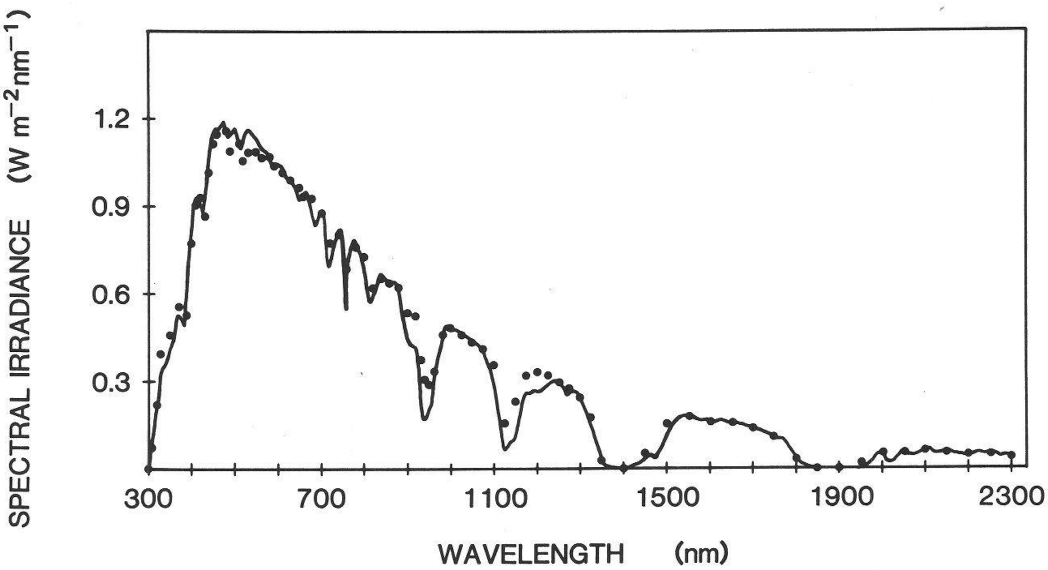

Fig. 3. Comparison of measured global spectral irradiance (—, redrawn after Bird et al. 1983) at Golden, Colorado (USA) on August 5, 1981 at 15h09 MST with corresponding calculated spectral values (●).

position. The equipment was situated on the roof of the Institute of Plant Biology at Zürich (CH, 8°33′ east longitude, 47°23′ north latitude, 455 m altitude). The horizontal global irradiation was simultaneously recorded by a second pyranometer situated close by.

To model the radiation data, the atmosphere and aerosol models MIDSUM and RURAL were used. For choosing an appropriate meteorological range the calculated horizontal values were compared with the corresponding data of the two pyranometers. Sea-level meteorological ranges between 15 and 50 km gave good fits for all days.

Fig. 4 shows the measured and calculated results for different slope angles of the receiving surface in the sun's vertical, i.e. 180° azimuth angle to the direction of the sun. The calculation were performed for the May 11. Differences in the irradiation arising from the variation of the solar-earth distance between April 15 and July 7 amount to ±1.3% respectively. To model the reflected radiation incident from the foreground on the inclined planes the data set for general soils and rocks (ALLSOIL) is used as mentioned above. The uncertainty of the measured values is expected to be about 5% as long as the angle of incidence of the direct radiation is smaller than 75°. The difference between the computation and most measured values is within 5%.

For ecophysiological investigations, especially in connection with photosynthesis research, the portion of photosynthetically active radiation (PAR) of irradiation is of great importance. Stanhill and Fuchs (1977) performed measurements of the ratio η of PAR to total global radiation for different ranges of the solar zenith angle at Bet Dagan.

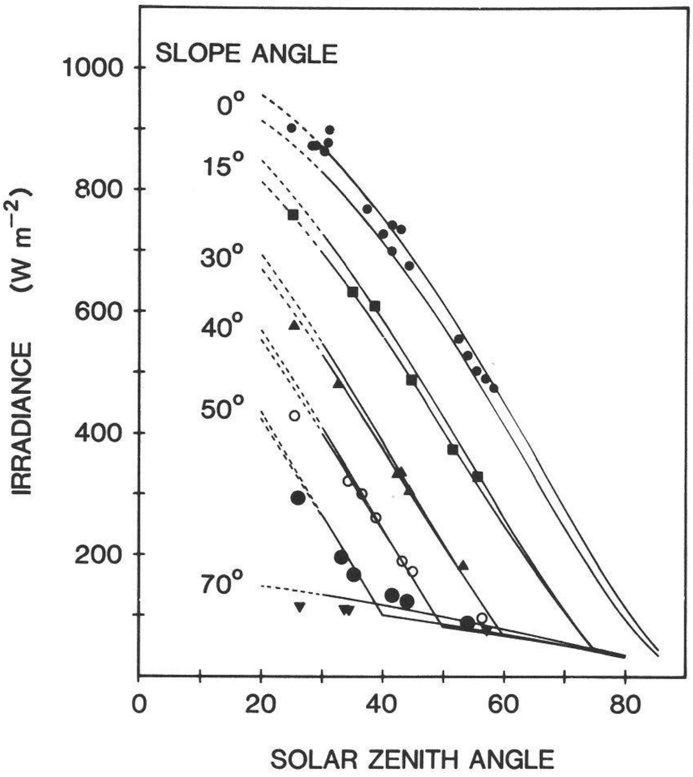

Fig. 4. Measured (symbols) and calculated (solid lines) global irradiation on planes with different slope angles in the sun's vertical (180° azimuthal difference to the sun) as a function of solar zenith angle. The calculation was performed for 15 km (lower solid lines) and 50 km (upper solid lines) sea-level meteorological ranges.

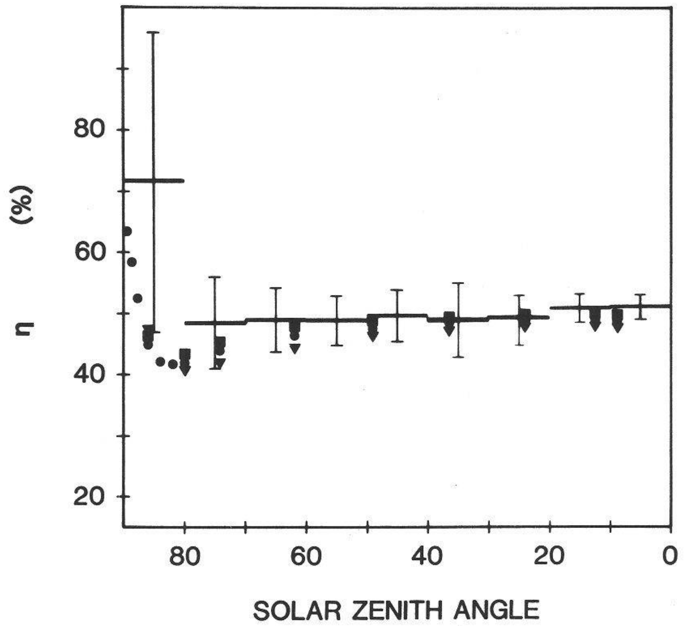

Fig. 5. Measured ratio η of PAR to global radiation (horizontal bars with standard deviation) as a function of solar zenith angle ranges (redrawn after Stanhill and Fuchs 1977) and corresponding values calculated for 12 km (▼), 23 km (●) and 50 km (■) sea-level meteorological range.

They defined η by

$$\eta = \int_{220}^{686} G(\lambda)\, d\lambda \Big/ \int_{220}^{3000} G(\lambda)\, d\lambda \tag{12}$$

where $G(\lambda)$ is the global radiation at wavelength λ [nm]. In Fig. 5 the ranges of η determined by Stanhill and Fuchs (1977) are given together with the corresponding calculated values. The atmosphere and aerosol models MIDSUM, MODMISU and RURAL were used. The calculations were performed for 12 and 50 km sea-level meteorological range with MIDSUM and for 23 km with MODMISU. There is a good correlation with the data of Stanhill and Fuchs (1977) up to solar zenith angles of 75°. Above 75° the uncertainty in both measurement and calculation grows quickly. The calculated data show also that there is little difference in η with changing turbidity or climatic conditions. This statement agrees with the results of Szeicz (1975).

Discussion and conclusion

By comparing different kinds of measured and calculated radiation data it has been shown that the proposed calculation program ECOSOL gives a good modeling of clear sky global irradiation and its spectral power distribution. It can also be expected that the calculation of actual lighting conditions for different orientations of the receiving surface is reliable. The comparisons made for different sites show that the program is applicable for different geographical locations.

The approached solution using pyranometer or quantum sensor data, e.g. the diurnal course of global irradiation, for the estimation of the appropriate sea-level meteorological range, i.e. to characterize the actual turbidity conditions, is suitable for ecophysiological applications as the equipment for such research is usually supplied with one of the mentioned instruments. The direct and diffuse component are more sensitive to the turbidity than the global radiation as Gueymard (1989) shows. It is therefore recommended to use global *and* diffuse horizontal data for the determination of the meteorological range. But as the use of the programm is designed for clear conditions, i.e. meteorological ranges greater than 15 km, good results can anyway be expected.

As was demonstrated by the comparisons between measured and calculated data, the modeling of total global irradiance on planes with different aspects agree with 5% with actual values. This statement is valid provided the solar zenith angle is smaller than 75° or the portion of diffuse radiation is not more than 50% of global radiation. For the diffuse radiation an accuracy of 10% can be expected. The computation of diffuse sky radiation and above all equations (3) and (4) can be approved, by more and very accurate simultaneous measurements of clear-sky diffuse radiation and global radiation. Unfortunately there are not many appropriate data available in literature. The mentioned values of uncertainty are valid when at thermopile pyranometer is used for adjusting the calculated horizontal global irradiation. The silicon cell pyranometers and quantum sensors frequently used by ecologists are less accurate.

The modeling of spectral distribution in connection with absorption properties of plant tissue and special reflection properties of the environment and its ecophysiological applications will be demonstrated in a second and third paper (Eller and Flach 1990, Flach and Eller 1991).

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