Agricultural and Forest Meteorology, 38 (1986) 217—229
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

SEPARATING THE DIFFUSE AND DIRECT COMPONENT OF GLOBAL RADIATION AND ITS IMPLICATIONS FOR MODELING CANOPY PHOTOSYNTHESIS
PART I. COMPONENTS OF INCOMING RADIATION

C.J.T. SPITTERS[1], H.A.J.M. TOUSSAINT[1] and J. GOUDRIAAN[2]

[1] *Foundation for Agricultural Plant Breeding, SVP, P.O. Box 117, 6700 AC Wageningen (The Netherlands)*

[2] *Department of Theoretical Production Ecology, Agricultural University, P.O. Box 430, 6700 AK Wageningen (The Netherlands)*

(Received October 24, 1985; revision accepted May 13, 1986)

ABSTRACT

Spitters, C.J.T., Toussaint, H.A.J.M. and Goudriaan, J., 1986. Separating the diffuse and direct component of global radiation and its implications for modeling canopy photosynthesis. Part I. Components of incoming radiation. Agric. For. Meteorol., 38: 217—229.

In modeling canopy photosynthesis, it is important to discriminate between the direct and diffuse components of incoming, global radiation. An equation is presented to estimate the share of both components from the measured daily global irradiance only. In this equation the share of the diffuse component is related to the ratio between global and extra-terrestrial radiation. This relation is based on a summary of literature data and of radiation measurements in The Netherlands. The diurnal trends of global, direct and diffuse radiation were derived from a sinusoid with a correction depending on solar angle. The random variation around this sine wave is characterized. For clear skies about 15% of the diffuse flux comes predominantly from directions near the sun and this circumsolar component has to be added to the direct flux. On the other hand, for clear skies the diffuse fraction in the photosynthetically active wave bands is about 40% larger than that for the total global radiation. In the past, the partitioning between direct and diffuse radiation was tackled by assuming that short periods of either fully clear or overcast conditions alternate within the day. That approach severely underestimated the share of the diffuse component in the total global radiation. The method presented in this paper is particularly useful for application in crop growth models.

INTRODUCTION

Canopy photosynthesis can be calculated from the amount of light absorbed by the canopy and the photosynthesis—light response of the leaves. If the light absorption were averaged over the canopy and over the considered time interval, canopy photosynthesis would be overestimated because of the convex, asymptotic response of photosynthesis. In most crop growth models, the spatial and temporal variation in illumination intensity of the leaves is therefore accounted for in some way (e.g. Duncan et al., 1967; de Wit et al., 1978; van Keulen et al., 1982; Hari et al., 1984). However, in none of these

0168-1923/86/$03.50

models is the partitioning of the irradiance into its direct and diffuse component treated satisfactorily. The usual way of tackling this partitioning is to assume that within the day short periods of either clear or overcast conditions alternate (de Wit, 1965). It will be shown that this approach is not adequate.

With modeling of canopy photosynthesis in view, Weiss and Norman (1985) and Lantinga (1985) presented a method to estimate the diffuse and direct radiation components from the measured total daily irradiance, based on the potential amount of radiation which may reach the earth surface. In the present paper, we present a different and more straightforward method, which is based on the ratio between measured daily irradiance of the earth surface and calculated radiation outside the atmosphere. The method is based on literature dealing with radiation in relation to its use in solar collectors. Quantification of the relationships relies mainly on weather data for The Netherlands: measurements for de Bilt 1961—1977 (summarized by de Jong, 1980) and measurements for Wageningen 1977—1982 (Dept. Physics Meteorol., 1977—1982). In Part II, the established radiation relationships will be incorporated into a model to calculate daily canopy photosynthesis.

DESCRIPTION OF THE MODEL FOR INCOMING RADIATION

Daily values of the global irradiance are input for the model. The global radiation is partitioned into a direct and diffuse flux on the basis of the fraction of the total radiation which has been transmitted through the atmosphere. Instantaneous values are derived from the daily totals by applying a modified sinusoid over the day. The variation around this sine wave is discussed.

Separating the diffuse and direct flux out of the global irradiance.

The radiation incident upon the earth surface is partly direct, with angle of incidence equal to the angle of the sun, and partly diffuse, with incidence under different angles. The diffuse flux arises from scattering (reflection and transmission) of the sun's rays in the atmosphere. The share of the diffuse flux will therefore be related to the transmission of the total radiation through the atmosphere. This atmospheric transmission is measured by the ratio between the global radiation incident upon the earth surface (S_g) and the radiation just outside the atmosphere (S_o).

The extra-terrestrial irradiance at a plane parallel to the earth surface proceeds with the sine of the solar altitude according to:

$$S_o = S_{cs}[1 + 0.033 \cos(360 t_d/365)] \sin\beta = S'_{sc} \sin\beta \qquad (1)$$

where S_o = extra-terrestrial irradiance ($J\,m^{-2}\,s^{-1}$); S_{sc} = solar constant ($1370\,J\,m^{-2}\,s^{-1}$; I.E.A., 1978); $\sin\beta$ = sine of elevation of the sun above the

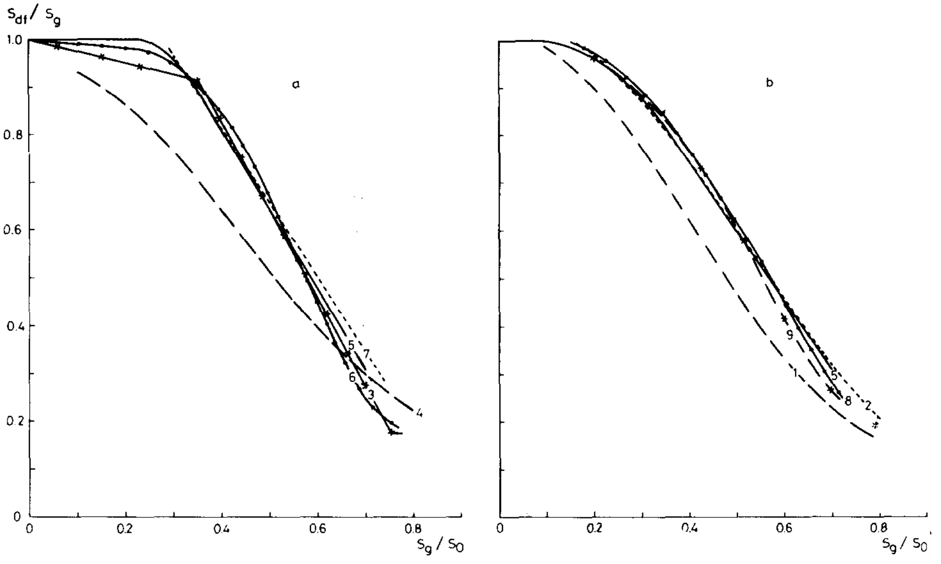

Fig. 1. Relation between share of diffuse flux in global radiation (S_{df}/S_g) and atmospheric transmission (S_g/S_o) for (a) hourly and (b) daily radiation values. Regression equations as presented in the references were applied, except for refs. 1 and 2 where equations are according to ref. 4, and for ref. 5 (daily data), 7 and 8 where we calculated the regression from the data. References with location: 1. Liu and Jordan (1960, Mass. U.S.A.), 2. Ruth and Chant (1978, four Canadian cities), 3. Orgill and Hollands (1977, Toronto, Canada), 4. Bruno (1978, Hamburg, W. Germ.), 5. de Jong (1980, de Bilt, Netherlands), 6. Erbs et al. (1982, four U.S.A. locations), 7. van den Brink (1982, Cabauw, Netherlands), 8. Dept. Physics Meteor. (1977—1982, Wageningen, Netherlands), 9. Collares-Pereira and Rabl (1979, five U.S.A. locations).

horizon (eq. 15). The cosine expression (in degrees) accounts for the yearly course of the distance between earth and sun, where t_d refers to the day since 1 January.

Relationships between the share of the diffuse flux in the global irradiance (S_{df}/S_g) and the atmospheric transmission (S_g/S_o) are found in several research reports concerning the use of solar energy in solar collectors. The observed relationships are summarized in Fig. 1. The relation is characterized by an approximately linear trend for transmissions ranging between 0.35 and 0.75. At low transmissions, nearly all of the incoming radiation is diffuse so that the curve bends off.

There appears to be some variation among the published relations (Fig. 1), arising from differences in atmospheric conditions, especially relative sunshine duration, water content of the atmosphere, and cloud type, but also lack of fit of the presented regression equation from the data and differences in the method of measuring the diffuse radiation. The diffuse flux can be determined as the difference between measured global and direct radiation.

It is easier, however, to measure the diffuse irradiance by means of a shadow band, in which case, correction has to be made for the part of the sky which is covered by the shadow band (correction methods by Dehne, 1984). The Wageningen measurements of diffuse irradiance were carried out with a cylindric shadow band of 5 cm width and 25 cm radius (A.D. Welgraven, personal communication). Application of the method proposed by Dehne (1984) yielded on the average a correction of 15% (Fig. 2a). Hence neglecting this correction would mean a substantial underestimation of the diffuse component and this was the cause of the deviating results of Liu and Jordan (Collares-Pereira and Rabl, 1979) (Fig. 1b).

It is important to consider the time interval for which the radiation totals are measured: the longer this interval, the smaller the calculated ratio between diffuse and global radiation at a given transmission. Hence the fraction diffuse calculated from daily radiation values (Fig. 1b) is smaller than that based on hourly values (Fig. 1a). In the data set of de Bilt (de Jong, 1980, p. 79, 80), the fraction diffuse at an atmospheric transmission of 0.4 was 0.81 when hourly values were involved, 0.74 when daily values, and 0.63 when monthly radiation values were used. This effect is because (1) higher transmissions contribute more to the radiation totals due to their greater energy level, and (2) averaging is performed over a non-linear, convex relationship (Fig. 1). For example, when 2 h of equal S_o have $S_g/S_o = 0.3$ and 0.7 and $S_{df}/S_g = 1.0$ and 0.3, respectively, then the share of the diffuse flux over this 2-h period is $\bar{S}_{df}/\bar{S}_g = 0.51$ while the arithmetic mean of the shares is $\overline{S_{df}/S_g} = 0.65$.

The three Dutch data sets of de Bilt, Cabauw and Wageningen agree very well with each other (Fig. 1). The relations for de Bilt and Cabauw are both based on measurements of direct radiation, but that for de Bilt embraces more years. We recommend therefore the relation as established for de Bilt (de Jong, 1980, p. 79):

$$S_{df,d}/S_{g,d} = 1 \qquad \text{for} \qquad S_{g,d}/S_{o,d} < 0.07 \qquad (2a)$$

$$S_{df,d}/S_{g,d} = 1-2.3\,(S_{g,d}/S_{o,d} - 0.07)^2 \qquad \text{for } 0.07 \leqslant S_{g,d}/S_{o,d} < 0.35 \qquad (2b)$$

$$S_{df,d}/S_{g,d} = 1.33-1.46\,S_{g,d}/S_{o,d} \qquad \text{for } 0.35 \leqslant S_{g,d}/S_{o,d} < 0.75 \qquad (2c)$$

$$S_{df,d}/S_{g,d} = 0.23 \qquad \text{for } 0.75 \leqslant S_{g,d}/S_{o,d} \qquad (2d)$$

where S_{df}, S_g and S_o denote the diffuse, global and extra-terrestrial radiation, respectively. The subscript d refers to daily values. $S_{o,d}$ is obtained from eq. 1 and 18. A corresponding set of equations for hourly values is given in eq. 20. The relationships are remarkably constant over climates and latitudes (Fig. 1; Collares-Pereira and Rabl, 1979; Erbs et al., 1982) so that the presented equations will be valid for a wide range of conditions.

There is substantial variation around these regressions. For hourly values, de Jong (1980, p. 63) reported a standard deviation of 0.10 for the individual values around the mean trend. For daily values, the deviation was smaller. Applying eq. 2 to the Wageningen data resulted for the ratio between the observed and predicted fraction diffuse in a standard deviation of 0.15, partly due to a systematic deviation from the de Bilt regression (curve 8 against 5 in Fig. 1b).

An important part of the variation around the relation given in eq. 2 is explained by differences in relative sunshine duration (Fig. 2b). Both de Jong (1980) and van den Brink (1982) found that the fraction diffuse was predicted even slightly better from the relative sunshine duration than from the atmospheric transmission. The close relation with relative sunshine duration is due to the phenomenon that clouds partly operate as an on-off switch for direct radiation. Predicting the fraction diffuse from relative sunshine duration has, however, the disadvantage of requiring this duration as additional input variable in crop growth models.

The seasonal influence on eq. 2 is small (de Jong, 1980, p. 65, 66, A22; Erbs et al., 1982).

Diurnal trend of global, diffuse and direct radiation

The regular, diurnal trend of the irradiance is derived from the daily total of global radiation and the daily course of extra-terrestrial radiation. As a first approximation, we suppose the atmospheric transmission constant during the daylight period:

$$S_g/S_o = S_{g,d}/S_{o,d} \tag{3}$$

where the subscript d refers to the daily total of global and extra-terrestrial radiation. Substitution of eq. 1 for the daily course of extra-terrestrial radiation gives for the instantaneous global radiation

$$S_g = \sin\beta\, S_{g,d}/\int(\sin\beta \mathrm{d}t) \tag{4}$$

The daily integral of the sine of the solar altitude β has been worked out in eq. 18.

A more sophisticated approach is to account for the daily course in atmospheric transmission. Transmission is lower near the margins of the daylight period because of haze in the morning and incoming clouds in the afternoon. This effect is greater than that of increase in path length through the atmosphere at lower solar heights. Thus, the diurnal trend in transmission is related to solar height. Data of de Bilt (de Jong, 1980, p. A39) point to a convex asymptotic relation within the day between transmission and $\sin\beta$. In order to keep calculation simple, we approximate this with the linear relation

$$S_g/S_o = a + b\sin\beta \tag{5}$$

where a and b are empirical regression coefficients. Integration of S_g over the day gives the daily irradiance $S_{g,d}$ as a function of, among others, the coefficient a. Substitution of the resulting expression for a into eq. 5 gives for the instantaneous global radiation

$$S_g = \sin\beta(1 + (b/a)\sin\beta)S_{g,d}/\int[\sin\beta(1 + (b/a)\sin\beta)\,\mathrm{d}t] \tag{6}$$

The integral has been worked out for $b/a = c$ in eq. 19. For the de Bilt data (de Jong, 1980, p. A39) b/a was about 0.4 for that part of the day where β exceeds 20°. The model was rather insensitive to the choice of the value of b/a.

Eq. 5 is in fact a simplification of the expression suggested by Collares-Pereira and Rabl (1979), and when applied to the de Bilt data both equations performed equally well.

The transmission coefficient for diffuse radiation (S_{df}/S_o) is quite insensitive to cloud conditions and solar height (Collares-Pereira and Rabl, 1979). The instantaneous diffuse flux is thus estimated as

$$S_{df} = S_o S_{df,d}/S_{o,d} \qquad S_{df} \leqslant S_g \tag{7}$$

This equation was in accordance with the de Bilt data.

The instantaneous direct flux is obtained from eqs. 6 and 7 as

$$S_{dr} = S_g - S_{df} \tag{8}$$

Circumsolar part of diffuse radiation

For a uniform overcast sky, the diffuse irradiance is "isotropic", i.e. irradiance intensity is independent of angle. For a clear sky, the diffuse flux is, however, anisotropic. Due to the predominantly forward-directed Mie scattering of aerosols, there is a higher intensity into the direction of the sun. This circumsolar radiation has to be subtracted from the diffuse flux and added to the direct flux.

For a horizontal plane under a clear sky, the circumsolar part equals $\cos^2(90° - \beta)\cos^3\beta$ times the remaining part of the diffuse flux (Temps and Coulson, 1977). To interpolate to intermediate sky conditions, Klucher (1978) found that this factor has to be multiplied by $1 - (S_{df}/S_g)^2$. The fraction diffuse adjusted for circumsolar radiation therefore becomes

$$S'_{df,d}/S_{g,d} = (S_{df,d}/S_{g,d})/\{1 + [1 - (S_{df,d}/S_{g,d})^2]\cos^2(90° - \beta)\cos^3\beta\} \tag{9}$$

where $S_{df,d}/S_{g,d}$ is the unadjusted fraction diffuse (eq. 2). Hence at an average solar angle β of 45° and a very clear sky, 15% of the total diffuse flux consists of circumsolar radiation. It can be derived from eq. 9 that this percentage is quite insensitive to the normal range of daily averages of β.

Photosynthetically active radiation

Up to now global radiation (300—3000 nm) has been considered, but only the 400—700 nm wavebands are photosynthetically active (PAR); the fraction PAR amounts to 0.50 and is remarkably constant over different atmospheric conditions and solar elevation, provided that β is $> 10°$ (Szeicz, 1974).

Under an overcast sky, radiation is scattered by clouds. Under a very clear sky, however, scattering is predominantly by individual molecules of nitrogen, oxygen and other gases (Rayleigh scattering). The degree of scattering is then inversely proportional to a power function of wavelength. Hence, for a clear sky, the scattered diffuse component in the photosynthetically active wavebands is bigger than that in the total global radiation. This is illustrated by measurements of Burtin et al. (1981) where for clear skies the fraction diffuse at 700 nm and 1000 nm was 32 and 18%, respectively, of that at 400 nm. From their extensive measurements it appears that for clear skies the fraction diffuse in the PAR region is 1.4 times the fraction diffuse of the total global radiation.

Photosynthetic activity is almost twice as great in the red part as in the blue part of the spectrum. Weighting the irradiance in the different wavebands to the action spectrum of photosynthesis (e.g. Jones, 1983, p. 16) reduced the above factor to 1.3. The fraction diffuse in the PAR wavebands is thus obtained from the fraction diffuse of global radiation (eq. 9) as:

$$PAR_{df,d}/PAR_d = [1 + 0.3\,(1 - (S_{df,d}/S_{g,d})^2)]\,(S'_{df,d}/S_{g,d}) \tag{10}$$

where the subscript d points to daily totals. The second part of the expression was introduced to interpolate to intermediate sky conditions.

The corrections to account for circumsolar radiation (eq. 9) and a greater diffuse part in the PAR wavebands (eq. 10) largely outweighted each other (Fig. 2a) so that in a simple model both may be neglected.

Variation in irradiance around diurnal sine wave

Verdonschot and van den Brink (1982) supply standard deviations of 6-min radiation totals relative to the corresponding hourly means for Cabauw Sept. 1980—Oct. 1981. The standard deviation (σ) relative to the mean decreased linearly with the hourly global irradiance according to

$$\sigma_{S_g}/S_g = 0.37 - 0.00036\,S_g \tag{11}$$

with the hourly mean S_g in $J\,m^{-2}\,s^{-1}$. In this way a normal distribution around the diurnal sine wave is defined.

The random variation in irradiance is probably better decribed by considering the variation in hourly transmission. This transmission S_g/S_o will follow a skew distribution with zero as lower bound and a value of about 0.8 as upper bound. Further research on the variation in radiation around the diurnal sine wave is needed.

Separating clear and overcast skies?

In crop growth models, the random variation in irradiance and the partitioning into the direct and diffuse flux are usually tackled by assuming the sky to be either clear or overcast (de Wit, 1959, 1965; Duncan et al., 1967; applications in crop growth models of e.g. de Wit et al., 1978; van Keulen et al., 1982; Ng and Loomis, 1984). Hence, it is supposed that clouds operate just like an on-off switch for the direct flux. For an overcast sky, all

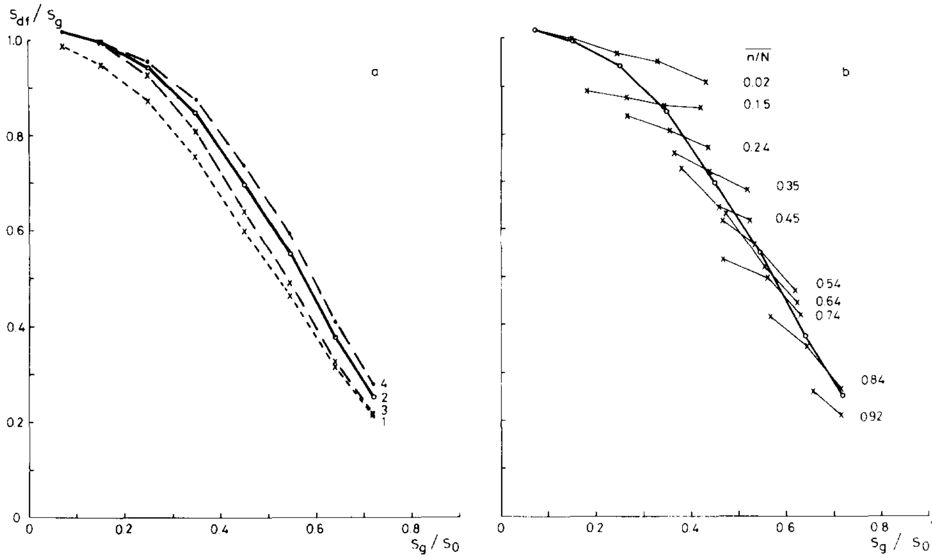

Fig. 2. Relation between share of diffuse flux in global radiation (S_{df}/S_g) and atmospheric transmission (S_g/S_o) for daily radiation values of Wageningen 1977—1982. Represented are means of intervals of 0.1 S_g/S_o. (a) Plot showing the different correction procedures: (1) uncorrected data, (2) data adjusted by the procedure of Dehne (1984) for shade effect of shadow band, (3) as (2) but minus circumsolar part of diffuse radiation (eq. 9), (4) estimated relation for photosynthetic active wave bands (eq. 10). (b) Plot showing the influence of relative sunshine duration (n/N) on the share of the diffuse flux (data adjusted for influence of shadow band). Data are given for intervals of 0.1 relative sunshine duration. Each interval is represented by its mean. Thick curve is identical to curve (2) of plot (a).

irradiance is diffuse, whereas for a clear sky a certain fraction is diffuse, and the remainder is direct. The fraction that the day is overcast is estimated from the measured daily global radiation in relation to the irradiance for a standard clear and a standard overcast day. It will, however, be demonstrated that this approach is not justified. Lantinga (1985) noted already that the approach underestimated the fraction diffuse in the incoming radiation.

For the Wageningen data, daily global irradiance ($S_{g,d}$) depended on relative sunshine duration according to the linear regression equation

$$S_{g,d}/S_{o,d} = 0.20 + 0.56\,n/N \qquad (r^2 = 0.84) \tag{12}$$

where $S_{o,d}$ = daily extra-terrestrial irradiance (eq. 1 and 18); n/N = daily duration of bright sunshine (measured with a Campbell—Stokes recorder) relative to daylength. These coefficients agree well with the values given by Frère and Popov (1979). Thus, a standard clear sky ($n/N = 1$) and a standard overcast sky ($n/N = 0$) are characterized by irradiance:

$$S_{cl,d} = 0.76\,S_{o,d} \quad \text{and} \quad S_{ov,d} = 0.20 S_{o,d} \tag{13}$$

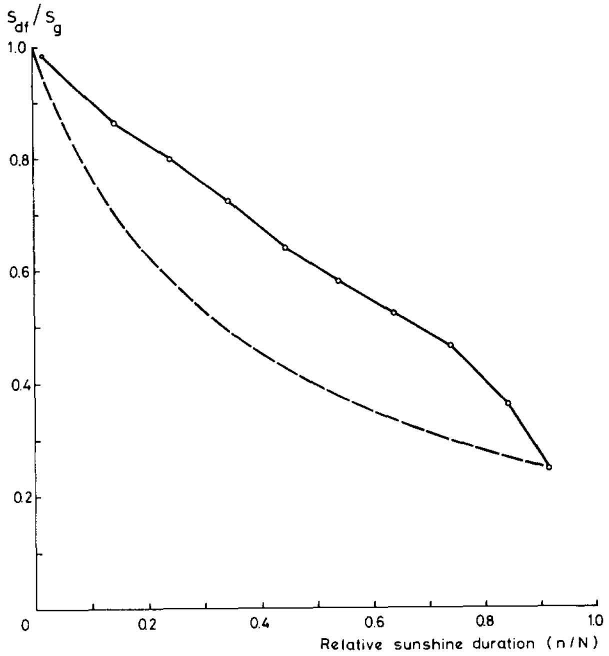

Fig. 3. Relation between share of diffuse flux in global radiation (S_{df}/S_g) and relative sunshine duration (n/N) for daily radiation values of Wageningen 1977–1982 (data corrected for influence of shadow band). Solid curve connects the actual means of intervals of 0.1 n/N. The broken curve represents the relation expected if clouds had a strict on–off influence on the direct flux and was obtained by dividing eq. 4 by eq. 12.

respectively. Under a standard overcast sky all irradiance is diffuse. Under a standard clear sky, 77% of global irradiance is direct and the other 23% diffuse (Fig. 3, eq. 2c).

Hence, if the sky were either clear or overcast (the on–off switch hypothesis), the daily diffuse flux ($S_{df,d}$) would depend on relative sunshine duration according to

$$S_{df,d}/S_{o,d} = 0.23 \times 0.76(n/N) + 0.20\,[1 - (n/N)] \qquad (14)$$

Division by eq. 12 gives estimated fraction diffuse ($S_{df,d}/S_{g,d}$), which is represented by the broken curve in Fig. 3. This predicted relation, however, strongly underestimated the measured fraction diffuse (solid curve in Fig. 3). For example, for an intermediate sky ($n/N = 0.5$), the on–off switch hypothesis predicts a fraction diffuse of 0.39, where 0.61 was actually observed (Fig. 3). Hence, for partly overcast skies, during the sunny periods a greater part of the irradiance appears to be scattered compared to standard clear days.

That reality is more intermediate also implies that the assumption of a sky being either clear or overcast overestimates the random variation in irradiance. Owing to the underestimation of the diffuse flux (Fig. 3) and to the overestimation of the random variation in global irradiance, models based on the assumption of a strict on—off switch of clouds underestimate canopy photosynthesis as will be demonstrated in part II. Thus, separation of direct and diffuse radiation should not be based on the assumption of an on—off switch operated by clouds for direct radiation but on the relationship presented in Fig. 1 and eq. 2.

APPENDIX

The sine of solar elevation β at hour t_h (solar time) is

$$\sin\beta = \sin\lambda \sin\delta + \cos\lambda \cos\delta \cos[15(t_h - 12)] \quad (15)$$

where λ = latitude of the site. Solar declination (δ in degrees) varies with the day of the year approximately according to:

$$\sin\delta = -\sin(23.45)\cos[360(t_d + 10)/365] \quad (16)$$

where t_d = number of day since 1 January. Daylength is

$$D = 12 + \frac{24}{180}\arcsin(\mathrm{tg}\lambda - \mathrm{tg}\delta) \quad (17)$$

with D in hours.

The integral of $\sin\beta$ over the day is obtained as twice the integral from sunrise ($\beta = 0°$) to solar noon ($\beta = 90° + \delta - \lambda$):

$$\int \sin\beta \, \mathrm{d}t_h = 3600[D\sin\lambda\sin\delta + (24/\pi)\cos\lambda\cos\delta(1 - \mathrm{tg}^2\lambda\,\mathrm{tg}^2\delta)^{1/2}] \quad (18)$$

having the dimension seconds. Similarly, the integral of $\sin\beta(1 + c\sin\beta)$ over the day is:

$$\begin{aligned}\int \sin\beta(1 + c\sin\beta)\mathrm{d}t_h = 3600\,[&D(\sin\lambda\sin\delta + c(\sin^2\lambda\sin^2\delta \\ &+ 0.5\cos^2\lambda\cos^2\delta)) \\ &+ (24/\pi)\cos\lambda\cos\delta(1 + 1.5c\sin\lambda\sin\delta) \\ &(1 - \mathrm{tg}^2\lambda\,\mathrm{tg}^2\delta)^{1/2}]\end{aligned} \quad (19)$$

The relation between fraction diffuse (S_{df}/S_o) and atmospheric transmission (S_g/S_o) recommended by de Jong (1980, p. 55) for hourly radiation values is:

$$S_{df}/S_g = 1 \qquad \text{for} \quad S_g/S_o \leqslant 0.22 \quad (20a)$$

$$S_{df}/S_g = 1 - 6.4(S_g/S_o - 0.22)^2 \qquad \text{for } 0.22 < S_g/S_o \leqslant 0.35 \quad (20b)$$

$$S_{df}/S_g = 1.47 - 1.66\,S_g/S_o \qquad \text{for } 0.35 < S_g/S_o \leqslant K \quad (20c)$$

$$S_{df}/S_g = R \qquad \text{for} \quad K < S_g/S_o \quad (20d)$$

with $R = 0.847 - 1.61\sin\beta + 1.04\sin^2\beta$ and $K = (1.47 - R)/1.66$.

ACKNOWLEDGEMENTS

We thank W.H. Slob (KNMI, de Bilt) and G.J. van den Brink (TNO-TH, Delft) for their valuable information.

DEFINITIONS OF SYMBOLS

		Unit	Equation
$a, b, c,$	Coefficients of the regression of transmission on solar angle		5
D	Daylength	h	17
K, R	Parameters in the regression of diffuse share on transmission		20
n/N	Relative sunshine duration	—	12
$\mathrm{PAR_d}$	Daily photosynthetically active radiation	$\mathrm{J\,m^{-2}\,d^{-1}}$	10
$\mathrm{PAR_{df,d}}$	Daily diffuse flux of photosynthetically active radiation	$\mathrm{J\,m^{-2}\,d^{-1}}$	10
$S_{\mathrm{cl,d}}$	Daily irradiance under a standard clear sky	$\mathrm{J\,m^{-2}\,d^{-1}}$	13
S_{df}	Diffuse flux of global radiation	$\mathrm{J\,m^{-2}\,s^{-1}}$	7, 20
S_{dr}	Direct flux of global radiation	$\mathrm{J\,m^{-2}\,s^{-1}}$	8
$S_{\mathrm{df,d}}$	Daily flux of diffuse radiation	$\mathrm{J\,m^{-2}\,d^{-1}}$	2
$S'_{\mathrm{df,d}}$	Daily diffuse flux adjusted for circumsolar radiation	$\mathrm{J\,m^{-2}\,d^{-1}}$	9
S_{g}	Global radiation (total irradiance at the earth surface)	$\mathrm{J\,m^{-2}\,s^{-1}}$	4
$S_{\mathrm{g,d}}$	Daily global radiation	$\mathrm{J\,m^{-2}\,d^{-1}}$	2
S_{o}	Extra-terrestrial irradiance on a plane parallel to the earth surface	$\mathrm{J\,m^{-2}\,s^{-1}}$	1
$S_{\mathrm{o,d}}$	Daily extra-terrestrial irradiance	$\mathrm{J\,m^{-2}\,d^{-1}}$	2
$S_{\mathrm{ov,d}}$	Daily irradiance under a standard overcast sky	$\mathrm{J\,m^{-2}\,d^{-1}}$	13
S_{sc}	Solar constant	$\mathrm{J\,m^{-2}\,s^{-1}}$	1
t_{d}	Number of day since 1 January	—	1, 16
t_{h}	Hour of the day (solar time)	h	15
β	Angle of sun above horizon	degrees	15
δ	Solar declination	degrees	16
λ	Latitude	degrees	15
$\sigma_{S_{\mathrm{g}}}$	Standard deviation of global radiation	$\mathrm{J\,m^{-2}\,s^{-1}}$	11

REFERENCES

Bruno, R., 1978. A correction procedure for separating direct and diffuse insolation on a horizontal surface. Solar Energy, 20: 97—100.

Burtin, M.B., Carels, M.R., Crommelynck, M.D. and Lemoine, M., 1981. Distribution spectrale du rayonnement solaire à Uccle, 2e semestre 1980. Inst. Royal Météor. Belgique, Misc. Serie B, No. 53.

Collares-Pereira, M. and Rabl, A., 1979. The average distribution of solar radiation-correlations between diffuse and hemispherical and between daily and hourly insolation values. Solar Energy, 22: 155—164.

De Jong, J.B.R.M., 1980. Een karakterisering van de zonnestraling in Nederland. Doctoraalverslag Vakgroep Fysische Aspecten van de Gebouwde Omgeving afd. Bouwkunde en Vakgroep Warmte- en Stromingstechnieken afd. Werktuigbouwkunde, Technische Hogeschool (Techn. Univ.), Eindhoven, Netherlands, 97 + 67 pp.

De Wit, C.T., 1959. Potential photosynthesis of crop surfaces. Neth. J. Agric. Sci., 7: 141—149.

De Wit, C.T., 1965. Photosynthesis of Leaf Canopies. Versl. landbouwk. Onderz. (Agric. Res. Rep.) 663, Pudoc, Wageningen, 57 pp.

De Wit, C.T. et al., 1978. Simulation of Assimilation, Respiration and Transpiration of Crops. Simulation Monograph, Pudoc, Wageningen, 140 pp.

Dehne, K., 1984. Diffuse solar radiation measured by the shade ring method improved by a correction formula. In: On Instruments and Observing Methods. WMO Rep. 15: 263—267.

Dept. Physics and Meteorology, 1977—1982. Maandoverzichten weergegevens Station Wageningen 'De Haarweg'. Vakgroep Natuur- en Weerkunde (Dept. Physics and Meteorology), Agric. Univ., Wageningen, Netherlands.

Duncan, W.G., Loomis, R.S., Williams, W.A. and Hanau, R., 1967. A model for simulating photosynthesis in plant communities. Hilgardia, 38: 181—205.

Erbs, D.G., Klein, S.A. and Duffie, J.A., 1982. Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation. Solar Energy, 28: 293—302.

Frère, M. and Popov, G.F., 1979. Agrometeorological Crop Monitoring and Forecasting. FAO Plant Production and Protection Paper 17, F.A.O. Rome, 64 pp.

Hari, P., Nilson, T., Salminen, R., Kaipiainen, L., Korpilahti, E. and Ross, J., 1984. Nonlinear dependence of photosynthetic rate on irradiance and its consequences for estimates of the amount of saccharides formed. Photosynthetica, 18: 28—33.

I.E.A., 1978. An Introduction to Meteorological Measurements and Data. Handling for Solar Energy Applications, Handbook Int. Energy Agency, Dept. Energy U.S.A., Washington D.C.

Jones, H.G., 1983. Plants and Microclimate. Cambridge Univ. Press, Cambridge, 323 pp.

Klucher, T., 1978. Evaluation of Models to Predict Insolation on Tilted Surfaces. N.A.S.A., TM-78842.

Lantinga, E.A., 1985. Productivity of grasslands under continuous and rotational grazing. Dissertation, Agric. Univ., Wageningen.

Liu, B.Y.H. and Jordan, R.C., 1960. The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. Solar Energy, 4: 1—19.

Ng, E. and Loomis, R.S., 1984. Simulation of Growth and Yield of the Potato Crop. Simulation Monograph, Pudoc, Wageningen, 147 pp.

Orgill, J.F. and Hollands, K.G.T., 1977. Correlation equation for hourly diffuse radiation on a horizontal surface. Solar Energy, 19: 357—359.

Ruth, D.W. and Chant, R.E., 1976. The relationship of diffuse radiation to total radiation in Canada. Solar Energy, 18: 153—154.

Szeicz, G., 1974. Solar radiation for plant growth. J. Appl. Ecol., 11: 617—636.

Temps, R.C. and Coulson, K.L., 1977. Solar radiation incident upon slopes of different orientations. Solar Energy, 19: 179—184.

Van den Brink, G.J., 1982. Climatology of solar irradiance on inclined surfaces. IV. Part II: Validation of calculation models. Technisch Physische Dienst TNO-TH (Inst. Applied Physics), Delft, Neth. Report 803.229 IV-2: 48 pp.

Van Keulen, H., Penning de Vries, F.W.T. and Drees, E.M., 1982. A summary model for crop growth. In: F.W.T. Penning de Vries and H.H. van Laar (Editors), Simulation of Plant Growth and Crop Production. Simulation Monograph, Pudoc, Wageningen, pp. 87—97.

Verdonschot, J.K.M. and van den Brink, G.J., 1982. Climatology of Solar Irradiance on Inclined Surfaces. IV. Part I: Measurements. Technisch Physische Dienst TNO-TH (Inst. Applied Physics), Delft, Neth. Report 803.229 IV-1: 107 pp.
Weiss, A. and Norman, J.M., 1985. Partitioning solar radiation into direct and diffuse, visible and near-infrared components. Agric. For. Meteorol., 34: 205—213.