Net radiation received by a horizontal surface at the earth

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B. de Jong
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The author, B. de Jong, graduated as a civil engineer at Delft University of Technology in 1969. During the last period of his studies he combined his studies with an assistantship in the chair of hydrology of this University. As such he also dealt with the calculation of evaporation, using Penman's theory. In searching for the radiation data required for such calculations, he found that much information on solar radiation is available in literature. The presentation of the radiation data, however, appeared to be widely different; moreover some references were not well known and often hard to obtain. It is De Jong’s merit that he traced all information available and compiled the data after critical examination and classification. Even after ending his assistantship in hydrology, he continued bringing up to date the material he collected. So his report became too extensive for publication in a hydrological or meteorological journal. Therefore I am very happy that this valuable material appears now as a monograph of Delft University Press. I am sure that this classified compilation of radiation data will be well appreciated and intensively used by hydrologists and meteorologists all over the world.

J. C. van Dam,
hydrology professor at Delft University of Technology
I. Introduction

One of the important methods of calculating the evaporation from a surface is to draw up a heat balance, introduced by Penman (1948). The heat balance, also called ‘energy balance’ or ‘radiation balance’, is written as follows:

\[ H = E + K + S + A \]  \hspace{1cm} (1)

where:
- \( H \) = net radiation received by a horizontal surface at the earth.
- \( E \) = part of the radiation energy used for evaporation (also called ‘latent heat flux’).
- \( K \) = turbulent heat exchange or sensible heat flux; this is the radiation energy transfer from the surface to the air (convection).
- \( S \) = heat flux through the surface and subsequent storage of heat in the soil.
- \( A \) = net subsurface flux of the horizontal transfer of heat (advective energy).

In many cases, when a longer period is considered (a month for example), \( S \) and \( A \) are assumed to be equal to 0. Hence,

\[ H = E + K \]

As the quotient \( K/E \) (Bowen’s ratio) can be calculated from physical theories concerning turbulent transfer, \( E \) can be compiled if \( H \) is known. If \( E \) is the main component of the heat balance, it can often be directly related to \( H \). For an example, see Linacre (1967).

\( H \) consists of the following components:

\[ H = R (1 - r) - R_b \]  \hspace{1cm} (2)

where:
- \( R \) = solar radiation energy reaching a horizontal surface on the earth = global radiation.
- \( r \) = reflection coefficient or albedo.
- \( R_b \) = effective long-wave radiation emitted by the surface.

Figure 1 gives a further explanation of the components of equation (2). This paper gives information about \( H \) and its components (equation 2). As far as possible, this information is world-wide.
Fig. 1. Average annual components of the heat balance for the system space-atmosphere-earth. The radiation values are expressed in kcal.cm.⁻² (after Perrin de Brichambaut (1968)).
2. Solar radiation reaching a horizontal surface at the earth (R)

2.1. DEFINITION OF SOLAR RADIATION (R)

Insolation, total radiation and total short wave flux or radiation are other terms for global radiation i.e. the total solar energy reaching the earth's surface (R). R is the sum of direct solar radiation (I) and sky radiation (D).

\[ R = I + D \]

Fig. 2. Components I and D of global radiation R.

Sky radiation is also termed 'scattered radiation', and 'diffuse radiation'. Direct radiation comes through the atmosphere direct on the earth’s surface. Scattered radiation reaches the earth’s surface via air particles and other particles in the atmosphere. Global radiation is sometimes called 'short wave radiation', because the sun emits only short wave radiation (see 2.2.1.).

2.2. FACTORS INFLUENCING THE AMOUNT OF GLOBAL RADIATION

The amount of global radiation depends on:
1. the solar constant.
2. the latitude of the location in question and the time of the year.
3. the influence of the atmosphere.
4. the albedo of the earth's surface.
5. the elevation of the location.
6. the time-unit.

2.2.1. SOLAR CONSTANT

The solar constant \( I_o \) is defined as the quantity of solar energy at normal incidence outside the atmosphere at the mean sun-earth distance. \( I_o \) is usually expressed in cal.cm\(^{-2}\).min\(^{-1}\).

Robinson (1966) has shown that the wave lengths of the solar radiation outside the
atmosphere range from about 0.20 μm to 7.0 μm (see fig. 3). The energy emitted in wave lengths shorter than 0.3 μm amounts to about 1% of the total energy emitted. This radiation is almost completely absorbed by the ozone layer at the top of the atmosphere.

The energy emitted in wave lengths longer than 3.0 μm amounts to about 20% of the total energy. This radiation is almost completely absorbed by water vapour and carbon-dioxide. Hence, the solar radiation that reaches the earth’s surface almost entirely consists of radiation with wave lengths from 0.3 μm to 3.0 μm.

![Spectrum of the solar radiation outside the atmosphere](image)

**Fig. 3.** Spectrum of the solar radiation outside the atmosphere (after Fritz (1957)). Curve P_{λ} shows the fraction of the total solar energy of wave lengths ≤ λ. The limits of the ultraviolet, visible and infrared regions are approximate.

The solar constant varies with time because the solar spectrum varies: the quantity of energy of one particular wave length is not constant. A correlation has been found between solar constant variations and the occurrence of sunspots. Current estimates of the solar constant ranges from 1.89 to 2.05 cal. cm⁻² min⁻¹.

For example, Nicolet (1951 a and b) has found 1.98, Johnson (1956) 2.00 and Murrey (1969) 1.92 cal.cm⁻² min⁻¹.

A major portion of the uncertainty arises from the possible accuracy of measurement. This accuracy is about 5%. The value 1.98 cal. cm⁻² min⁻¹ was recommended by the International Radiation Commission in its 1957 Toronto session and also in the International Instruction Manual for radiation measurements during the I.G.Y. (International Geophysical Year).

The solar constant is expressed in the International Pyrheliometric Scale 1956 (I.P.S. 1956). This scale is the most used today and is recommended by the Radiation Commission of I.A.M. (International Association of Meteorology) and the Working Group of W.M.O. (World Meteorological Organisation) at the joint International Conference at
Davos (Switzerland), in September 1956. Other important scales were: the Smithsonian scale (1913) and the original Angström scale (1905).

100 cal. Smithsonian 1913 = 98 cal. I.P.S. 1956
100 cal. Angström = 101.5 cal. I.P.S. 1956

2.2.2. LATITUDE OF LOCATION IN QUESTION AND TIME OF THE YEAR

The sun-earth distance and the position of the sun with regard to the earth's surface follow from the time of the year and the latitude of the location. The energy that reaches a plane at the top of the atmosphere above that station and at that time of the year can be computed from these data and the solar constant I_0.

2.2.3. INFLUENCE OF THE ATMOSPHERE

The influence of the atmosphere on the solar radiation can be subdivided into scattering and absorption.

Scattering is caused by air molecules, dust and other atmospheric pollution and by cloud particles. Part of the scattered radiation returns to space; another portion reaches the earth as sky radiation.

Solar energy is absorbed by the pure atmosphere, clouds, water and water vapour, dust, ozone and other gases in the atmosphere. The following figures give an impression of the relative amounts of the various components of radiation energy and the absorption. About 35 per cent of the energy reaching the earth's atmosphere is immediately reflected into space, mainly by clouds. Another 19 per cent is absorbed by the atmosphere. For a normal clear sky in Washington the sky radiation is about 16 per cent of the total when the sun is high and about 37 per cent when the solar elevation is about 10° (Fritz (1957)). The portion of sky radiation is generally larger in cloudy weather than on clear days. These figures are averaged and only give an indication.

The absorption by clear atmosphere depends on the wave length and the so called optical absolute air mass m, defined by:

\[ m = \frac{p}{1000} \]

where: \( p \) = air pressure in mb.
\( m_r \) = relative air mass, \( m_r = \frac{1}{\cos \theta} \)

\( m_r \) is the reciprocal value of the cosine of the zenith angle \( \theta \) of the sun. This means that \( m_r \) (as does \( m \)) increases with the path length through the atmosphere. The absorption by clear atmosphere is only a small part of the total absorption.

The absorption by clouds depends very much on the type of clouds. Clouds vary from thin, transparent cirrus, exerting little influence, to thick and dark thunderstorm clouds. In exceptional cases the absorption by the latter can reduce the solar energy reaching the earth to 1% of the normal value for some hours (Robinson (1966)). Dust, can absorb a considerable portion of the solar energy. Dust, water, water vapour, ozone and other gases absorb a quantity of solar energy, depending on the wave length. Water vapour mostly absorbs the greater wave lengths; which carry the largest fractions of the energy (Infra-red regions, see also fig. 2). This is why clouds are able to absorb much energy. It will be clear that air pollution reduces global radiation. In Rotterdam and its surroundings De Boer (1966) measured a decrease of 5-15% in global radiation with a clear sky \( R_d \) caused by air pollution.
Robinson (1966) amongst others gives complex formulae for these effects. No simple formulae are available.

2.2.4. EFFECT OF THE ALBEDO OF THE EARTH’S SURFACE

The albedo also influences the amount of \( R \) itself (indirect influence). This can be explained as follows. Part of the total radiation coming through the atmosphere reflects on the earth’s surface. This part can rescatter in the atmosphere. The diffuse radiation created in this way partly goes back to the earth. It is obvious that the effect of the albedo is greater in the case where the possibility of multiple scattering is greater, i.e. when the sky is partly cloudy, for example. When the sky becomes cloudy, the amount of direct radiation decreases, but the amount of sky radiation increases. In this way it can be explained that sometimes \( R \), on clear days, may be smaller than \( R \) on partly cloudy days. The difference also depends on the albedo.

To avoid misunderstanding, it should be recalled that our aim is to know the amount of solar energy available on the earth (i.e. \( R(1-r) \)). For this, one has to take into account the direct influence of the albedo on the global radiation \( R \) (i.e. the amount of solar energy reaching the earth’s surface).

2.2.5. ELEVATION OF LOCATION

The higher a location above sea level, the lower the air pressure and the shorter the path through the atmosphere, so the smaller the optical absolute air mass \( m \). The consequence is that less energy can be absorbed. Perrin de Brichambaut (1963) gives a correction of approx. 1% per 900 m increase in elevation. This correction is, of course, only an indication.

2.2.6. TIME-UNIT

The time-unit influences the amount of solar energy per ‘day’. The basis of time (a ‘day’) is not constant and the amount of energy is expressed in energy a day (in general, energy per period). A day is defined as the period between successive passages of the sun through a given meridian and is referred to as the real solar day. It is not constant due to a number of causes, such as for example the eccentricity of the orbit of the earth round the sun and the inclination of the ecliptic to the celestial equator (Robinson (1966)). The difference between a real solar day and a mean solar day is at the most around 1/10 for a short time only. Consequently this influence is of no importance, compared with the other effects, and has therefore been left out of consideration.

2.3. DIFFERENT METHODS OF PRESENTING DATA ON SOLAR RADIATION REACHING THE EARTH’S SURFACE

There are three different ways in which data on solar energy reaching the earth can be presented.
A. The amount of solar energy reaching the earth’s surface on cloudless days \( (R_d) \) is given, together with the influence of the cloudiness.
B. The amount of solar radiation reaching the outer limits of the atmosphere is given \( (R_o) \), together with a formula accounting for the influences of factors 3, 4 and 5,
listed in section 2.2. The time-unit influence is always left out of consideration. 
\( R_a \) includes the influences of factors 1 and 2 of section 2.2.

C. The amount of solar energy reaching the earth's surface (\( R \)), including all influences, is given directly.

2.3.1. METHOD A - SOLAR RADIATION ON CLEAR DAYS (\( R_{cl} \)) AND THE INFLUENCE OF THE RELATIVE DURATION OF SUNSHINE

2.3.1.1. Introduction

This method is the oldest for the compilation of solar radiation data. It was introduced by Ångström in 1924. Until now this method has been used in a relatively small number of cases. Computed values for \( R_{cl} \) are fairly reliable. However, this is laborious. The relationships between \( R_{cl} \) and \( R \) (the solar radiation reaching the earth's surface) are found from a number of measurements.

Fritz (1949) is one of the promotors of calculating \( R_{cl} \), see later. Ångström (1924) assumed the following linear relationship:

\[
R = R_{cl} (a' + (1 - a') \frac{n}{N}) \quad \text{(original Ångström formula)}
\]

\( R \) = daily total of global radiation
\( R_{cl} \) = daily total of global radiation when day cloudless
\( n \) = number of sunshine hours during that day
\( N \) = maximum possible number of sunshine during that day
\( a' \) = constant

Other authors have applied the same relationship; however, with a different unit of time, such as a month. Many authors have used the formula in the form

\[
R = R_{cl} (\alpha + \beta \frac{n}{N})
\]

\( \alpha + \beta \) should be equal to 1, according to Ångström. However, in some cases \( \alpha + \beta \) is not equal to 1, owing to different definitions of \( n \) and \( N \).

Four definitions of \( N \) are used:
1. \( N \) = time between astronomical sunrise and sunset.
2. \( N \) = time between local sunrise and sunset with regard to the natural horizon at the station in question.
3. \( N \) = maximum possible hours of sunshine recorded on a perfectly clear day by the recording instrument used.
4. \( N \) = time during which the sun's altitude is \( 3^\circ \) and higher.

The last definition is given by Perrin de Brichambaut (1963). The third definition is recommended by the Commission for Instruments and Methods of Observations of W.M.O. (1953). The difference between definition 1 or 2 and definitions 3 and 4 is due to the fact that the sunshine recorders have a small time-lag before recording, especially in the early morning and late afternoon.

Of the authors who give \( \alpha \)- and \( \beta \)-, or \( a \)- and \( b \)-values (subsection 2.3.2.), only Page

1. See below for the definition of \( N \).
(1964), Löf et al. (1966), Ångström (1965) and Perrin de Brichambaut (1963) have defined N precisely. Page and Löf et al. use definition 1, Ångström uses definition 3 and Perrin de Brichambaut definition 4. The other authors mentioned define N only as the maximum possible hours of sunshine. Fortunately, the influence of the definition of N is only small. Therefore, no further attention will be paid to this point.

2.3.1.2. Data

World maps of monthly $R_{d}$-data do not appear to have been made. Perrin de Brichambaut (1963) gives a table of estimated monthly values of $R_{d}$ as a function of latitude for the latitude range 70°N-30°S. He gives correction values for the elevation, water vapour, turbidity and albedo in order to correct the $R_{d}$-value for the station in question. A small table is given, showing $R/R_{d}$ as a function of $n/N$. From these data it is possible to compute $R$-values. However, this method is not handy, and also is only approximate.

Budyko (1956) and Berlyand (see Kondratyev (1969) p. 471) give a table of $R_{c}/R$-values as a function of latitude and months for the latitude range 0°-80°N. In this way one obtains $R_{d}$-values which are constant for a given latitude. The $R_{d}$ maps of the U.S.A. and Canada show that this is only a rough approximation (see map 1-12). Budyko and Berlyand use the following formula for computing $R$:

$$R = R_{d} \left[1 - (1 - k) C\right]$$  \hspace{1cm} \text{(Sawinoff-Ångström formula)}

where $k = \text{a constant that gives the relationship between solar radiation at an overcast sky and solar radiation on cloudless days.}$

$C = \text{average degree of cloudiness (tenths)}$

Budyko and Berlyand also give a table of mean latitudinal $k$-values for the latitude range 0°-85°N. These are used together with the $R_{d}$-values mentioned, which are also constant with the degree of latitude. Therefore, it is doubtful whether a result will be reached as accurately as that with the other methods mentioned.

The author has considered information on solar radiation on clear days ($R_{d}$) and the $\alpha$- and $\beta$-values, from the following countries (stations), listed in alphabetical order. The only information considered is where both $R_{d}$- and $\alpha$- and $\beta$-values are available, so that $R$ (our purpose) can be computed. For the $\alpha$- and $\beta$-values, see Table 1; for the values of $R_{d}$, see Table 2.

a. Australia

Hounam (1958) has found from two years of radiation records by four stations (Guilford, Darwin, Alice-Spring and Box Hill) $\alpha = 0.34$ and $\beta = 0.66$. As $R_{d}$-values were not available, Hounam assumed that the highest daily $R$-recordings for each month occurred on clear days. Of course, this is an approximation, but not a rough one, because Australia is near the equinox and clear days occur frequently. Hounam used the Australian radiation records of 1953 and 1954, published by the Commonwealth Bureau of Meteorology, which also publishes maps showing estimated monthly and annual sunshine records over Australia.

Funk (1965) gives the $\alpha$ and $\beta$ constants of Aspendale and Deniliquin. The values of Deniliquin have been computed from data given by De Vries (1958). Funk gives specific values for summer and winter. In this way it is possible to calculate $R$ more accurately. Table 2 gives the $R_{d}$-values. Aspendale's data are based on three years of recording and Deniliquin's on two years of record. Table 1 gives the $\alpha$- and $\beta$-values.
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<td>666</td>
<td>658</td>
<td>590</td>
<td>581</td>
<td>513</td>
<td>515</td>
<td>523</td>
<td>547</td>
<td>586</td>
<td>620</td>
<td>607</td>
<td>641</td>
</tr>
<tr>
<td>The Netherlands</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>De Bilt</td>
<td>52° 06'N</td>
<td>128</td>
<td>228</td>
<td>354</td>
<td>503</td>
<td>616</td>
<td>641</td>
<td>603</td>
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<td>386</td>
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<td></td>
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<tr>
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<td>59° 32'N</td>
<td>65</td>
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<td>295</td>
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<td>630</td>
<td>695</td>
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<td>530</td>
<td>355</td>
<td>200</td>
<td>75</td>
<td>35</td>
</tr>
</tbody>
</table>
b. Canada
Mateer (1955a) has constructed maps for average cloudless day insolation in langley's (1 langley = 1 cal.cm⁻²) for the 15th of each month (see map 1-12). The mean daily value for a certain month, which we mostly want to use, can be compiled in the following way.

The data given for the individual days for the location considered are plotted on an extended scale. A smooth curve is drawn through the points and from this curve one can compile the mean daily values for the desired month(s) quite accurately.

Mateer uses the calculation method of Fritz (July 1949) and also uses a number of measured values. Fritz uses the basic equation:

\[ Q_m = [1.94 \cdot (r_o/r)^2 \cdot \cos \theta (a_m'' + 0.5 - 0.5 a_m')] - D_m \]

where:
- \( Q_m \) = insolation in langley's per minute (cloudless sky).
- \( r_o \) = mean distance between earth and sun.
- \( r \) = actual distance between earth and sun.
- \( \theta \) = zenith angle of the sun (or angle of sun-rays to the vertical).
- \( a_m' \) = fraction of solar energy transmitted through the moist, clean atmosphere, considering depletion by scattering only.
- \( a_m'' \) = fraction of energy transmitted through the same atmosphere, considering both scattering and absorption.
- \( D_m \) = term including miscellaneous residual factors such as dust depletion, effect of ground reflection, etc.

Integrating the basic equation between sunrise and sunset yields the daily total of solar radiation.

\[ R_{cl} = F - D' \]

where:
- \( R_{cl} \) = daily total radiation (cloudless sky).
- \( F \) = summation of first term in right member of basic equation.
- \( D' \) = summation of \( D_m \).

The integrations are performed for an appropriate day. Therefore, \( a_m' \) and \( a_m'' \) depend only on the optical air mass \( m \) and on the precipitable water vapour \( w \) (\( w \) is defined as the depth of liquid which would result if all water vapour in a vertical column of air of unit cross section and atmosphere-high were condensed and collected at the bottom).

Kimball (1930) gives a chart relating \( a_m' \) and \( a_m'' \) to \( m \) and \( w \). \( m \) can be computed, \( w \) can be measured. \( \theta \) and \( r \) can be evaluated from astronomical data. In this way, \( F \) is computed. \(- D' \) is estimated in the following way. \( R_{cl} \) is evaluated from \( R \)-measurements by stations recording solar radiation. \( F \) is computed and \(- D' \) is found as: \(- D' = R_{cl} - F \). These \(- D'\)-values from the - relatively few - radiation-recording stations are plotted on maps and isolines of \(- D' \) are drawn. This is the critical point of the method: it is not possible to draw accurate isolines because of the few \(- D'\)-values. However, the value of \(- D' \) is mostly a small part of the value of \( F \), and so it is possible to construct fairly accurate maps for \( F \).

Mateer (1955 b) has found for Canada \( a = 0.355 \) and \( \beta = 0.68 \) in summer time. He gives the winter formula:

\[ R = R_{cl} [0.45 + 0.78 n/N (1 + 2.87 w_i^2)]. \]
\( w_i \) = the fraction of the total daylight period during which the sun is less than five degrees above the horizon.

c. Greece
Macris (1964, p. 454) has calculated for Athens \( \alpha = 0.34 \) and \( \beta = 0.63 \), based on four years of record. He has also computed the \( \alpha \)- and \( \beta \)-values for the individual months, so that the monthly values of \( R \) can be estimated more accurately (see table 1). The relevant radiation data on cloudless days (from Carapiperis (1964)) are given in table 2.

d. India
The global radiation on clear days has been computed for a number of Indian stations by the method given by Fritz (see Ramdas (1964) p. 423). The \( \alpha \)- and \( \beta \)-constants have been computed for only four of these stations by Venkiteswaran (1964) p. 497. These \( \alpha \)- and \( \beta \)-values are only based on the measurements during the International Geophysical Year (I.G.Y.). The data are reproduced in tables 1 and 2.

c. The Netherlands
Computations and data on the global radiation on cloudless days and the corresponding \( \alpha \)- and \( \beta \)-values have been given by De Vries (1955), based on records at Wageningen; and by De Boer (1961), based on records at De Bilt. The most recent and also the most accurate data, given by De Boer, have been reproduced (see tables 1 and 2). De Boer used the original Ångström formula:

\[
R = R_{cl} \left[ \alpha' + (1 - \alpha') \frac{n}{N} \right]
\]

He has used the formula for hourly amounts of global radiation, instead of daily or monthly amounts, as did the foregoing authors. He computed \( R_{cl} \)-values from measurements during the period 1954-1958. So he gives, for instance, 31 values of \( R \) in cal.cm\(^{-2}\) hour\(^{-1}\) for the one hour period 08.00-09.00 in January 1954. The \( R_{cl} \)- and \( \alpha' \)-values for an average day in January 1954 and the one hour period 08.00-09.00 were computed from the average of the measured 31 values of \( R \) and the corresponding \( n/N \)-measurements. And so on for all the one-hour periods during which global radiation is received. The method of the least squares has been used for these computations. The calculated \( \alpha' \)- and \( R_{cl} \)-values have been averaged for the five years of measurements.

The daily amount of \( R_{cl} \) for the average day of each month is found by summing up the hourly amounts. The \( \alpha' \)-value for the average day of each month is found by weighting the \( \alpha' \)-values with the corresponding \( R_{cl} \)-values. This weighting is essential. In this way the different influence of the clear sky during the course of the day, for example, is accounted for. The influence of the period of sunshine is received during the early morning and the late afternoon. Another day most of the sunshine is received during the middle hours of the day. It is clear that on the second day more global radiation is received than on the first day.

Computation with the aid of Ångström's formula would give the same amount (\( \alpha' \) and \( R_{cl} \) can be assumed to be constant during such a short period). This failure of Ångström's formula is clearly due to the fact that, in fact, \( \alpha' \) is some function of the sun's altitude. De Boer reduces the error by weighting the \( \alpha' \)-values and so he has found more accurate \( \alpha' \)-values. This example also shows the decreasing accuracy when the formulae and data given by the tables 1 and 2 are applied to periods shorter than one month.
De Boer has computed that with his method the standard deviation of the computed and
the observed daily amounts in each of the 12 months is reduced by 25% (De Bilt) and
18% (Wageningen), compared with the results obtained with the method given by De
Vries.

As the Netherlands is a small country with a fairly constant climate, the given data may
be applied to the whole country, without being very inaccurate. This is confirmed by the
global radiation maps given by Black (Northern Europe, see section 2.3.3.2.).

f. Sweden (Stockholm)
For Stockholm the amount of global radiation on clear days is given by Lindholm
(1959); based on measurements from 1941 to 1956.
   Ångström (1956) gives the corresponding α- and β-values (see table 1 and table 2).

g. United States of America
Fritz (1957) has constructed monthly maps of mean daily global radiation on cloudless
days. For the calculation method, see b. For computing the \( R_d \) - values he uses the ra-
diation data from 23 stations, averaged over several years. From the measurements of
11 stations he has computed \( \alpha = 0.35 \) and \( \beta = 0.61 \).

2.3.2. METHOD B – SOLAR RADIATION AT THE TOP OF THE ATMOSPHERE AND
INFLUENCE OF ATMOSPHERE, ALBEDO AND ELEVATION
The solar radiation reaching the top of the atmosphere (\( R_o \)) can be calculated accura-
tely. \( R_o \) is a function of latitude and time of the year only (the time-unit has not been
considered). The relationships between \( R \) and \( R_o \) can be found from measurements.
Method B has the advantage that \( R_o \) can be easily and accurately read from a table.
Laboratory calculations were needed to obtain \( R_d \), however, most investigators who
used method A, worked more accurately. They had to make a profound study to esti-
mate \( R_d \). In general they also compiled separately for the months (seasons) of the year.
Only in a few cases the authors who used method B made separate calculations for the
months (seasons).

2.3.2.1. Solar radiation at the top of the atmosphere (\( R_o \))
Original calculations of the solar radiation at the top of the atmosphere were found in
works by the following authors: Angot (1883) – see Brunt (1939) – Milankovitsch (1930)
based on Angot.

Angot computed the monthly totals as a function of the latitude. He used a solar con-
stant of 1.94 cal.cm\(^{-2}\).min\(^{-1}\). Shaw gives a table of the solar energy reaching the top of
the atmosphere in the middle of all weeks and on December 31 as a function of latitude.
Shaw's solar constant is 1.93 cal.cm\(^{-2}\).min\(^{-1}\), but the difference between the values of
Angot and Shaw is not constantly equal to 0.01/1.94, i.e. 0.5%. In view of the purpose of
this paper, the cause of this difference is not considered.

Robinson gives a table similar to Shaw's, but for a number of random days throughout
the year. He used a solar constant of 2.00 cal.cm\(^{-2}\).min\(^{-1}\). It is evident that the differ-
ence between the converted values of Shaw and Robinson is practically the same as
the difference between the solar constants used: 3.5%. For the highest latitudes, it is not possible to check this very accurately because of the few data given by Robinson, but the tendency is clearly the same.

The data given by Robinson for individual days have been plotted on an extended scale. Smooth curves were drawn and from these the mean monthly values were obtained. For the highest latitudes (70°, 80°, 90°) the data of Shaw have been used since in this case the number of days given by Robinson is insufficient to obtain accurate results. Shaw's values have been increased by 3.5%. The results are given in table 3.

Page (1964) and Schulze (1963) give tables of the total daily radiation reaching the outer limits of the atmosphere as a function of month and latitude. Both are based on Milankovitsch. Page used a solar constant of 2.00 cal.cm⁻².min⁻¹, Schulze uses 1.99 cal.cm⁻².min⁻¹. Page gives values only for the latitude range 40°N - 40°S, Schulze for the whole latitude range.

Table 4 gives a comparison of the values given by Angot, Robinson, Shaw and Milankovitsch, converted into one solar constant (2.00 cal.cm⁻².min⁻¹) and for a few latitudes. The Angot values are sometimes quite different from the others. The values given by Robinson, Shaw and Milankovitsch are practically the same, except for a few values at the highest latitudes. It is evident that Milankovitsch gives lower values than the others for those latitudes. The reason for this is not clear.

Finally, the values from Robinson and Shaw have been chosen by the present writer for the 'world table' (table 3), because these values are very similar and closest to the values given by Milankovitsch.

2.3.2. Influence of atmosphere, albedo and elevation

As the influences of albedo and elevation are small, compared with the influence of the atmosphere, all three influences are often summed up and called 'the influence of the atmosphere'. In the following formulae this has invariably been done.

Many authors give formulae for the influence of the atmosphere, albedo and elevation, mostly in the form:

\[ R = R_o (a + b \frac{n}{N}) \]

the so-called 'Ángström type'.

where: 
- \( R \): solar radiation reaching the earth's surface
- \( R_o \): solar radiation reaching the top of the atmosphere
- \( n \): actual duration of sunshine
- \( N \): maximum possible duration of sunshine during the same period.
- \( a \) and \( b \): constants.

Among the authors who give formulae which should be valid for a wide range of latitudes are: Black, Bonythan and Prescott (1954). They give:

\[ a = 0.23 \quad b = 0.48 \]

valid for latitudes in the range 65°N - 65°S, and compiled from a large number of measurements, for several years, taken from locations scattered all over the world.

1. See 2.3.1.1. for the definition of \( N \).
Table 3: Short-wave radiation flux at the top of the earth’s atmosphere (R<sub>0</sub>, cal.cm<sup>-2</sup>.day<sup>-1</sup>) as a function of month and latitude

<table>
<thead>
<tr>
<th>Month</th>
<th>Geographical latitude (degrees)</th>
<th>North</th>
<th>South</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90°</td>
<td>80°</td>
<td>70°</td>
</tr>
<tr>
<td>J</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>F</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>M</td>
<td>40</td>
<td>125</td>
<td>275</td>
</tr>
<tr>
<td>A</td>
<td>470</td>
<td>480</td>
<td>565</td>
</tr>
<tr>
<td>M</td>
<td>900</td>
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</tr>
<tr>
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<td>1075</td>
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<tr>
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<td>1010</td>
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<td>945</td>
</tr>
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<td>685</td>
</tr>
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</tr>
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</tr>
<tr>
<td>D</td>
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</table>


Value of the solar constant: 2.0 cal.cm<sup>-2</sup>.min<sup>-1</sup> I.P.S. 1956.
<table>
<thead>
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<th>60°N</th>
<th>0°</th>
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<td></td>
<td></td>
<td>A</td>
<td>S</td>
<td>M</td>
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<tr>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>February</td>
<td></td>
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<td>0</td>
<td>0</td>
</tr>
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<td>Station</td>
<td>Latitude</td>
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<td>Annual mean n/N-values</td>
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<td>------------------------</td>
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<td>Kampala</td>
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<td>0.46</td>
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<td>Stanleyville</td>
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<td>0.28-0.55</td>
<td>0.47</td>
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<tr>
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<td>0.41-0.84</td>
<td>0.58</td>
<td>0.34</td>
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<td>0.49</td>
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<td>0.30</td>
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<tr>
<td>Poona (dry)</td>
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<td>0.81</td>
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<tr>
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<td>0.65</td>
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<td>0.46</td>
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<tr>
<td>Bloemfontein</td>
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<td>0.25</td>
<td>0.50</td>
</tr>
<tr>
<td>Durban</td>
<td>29° 50' S</td>
<td>0.36-0.81</td>
<td>0.56</td>
<td>0.33</td>
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<td>0.67</td>
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<td>0.59</td>
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<td>Cape Town</td>
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<td>0.71</td>
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<td>Buenos Aires</td>
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<td>0.47-0.68</td>
<td>0.59</td>
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</tr>
<tr>
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<td>Albuquerque</td>
<td>35° 2' N</td>
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<td>0.78</td>
<td>0.41</td>
</tr>
</tbody>
</table>

1: Based on daily values of n/N, instead of monthly
11: Based on weekly values of n/N, instead of monthly

Continued on next page
<table>
<thead>
<tr>
<th>Station (region)</th>
<th>Latitude</th>
<th>Range of monthly mean values of n/N</th>
<th>Annual mean n/N-values</th>
<th>a</th>
<th>b</th>
<th>Source</th>
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<tr>
<td>Canberra</td>
<td>35° 17' S</td>
<td>—</td>
<td>—</td>
<td>0.25°</td>
<td>0.54°</td>
<td>Chidley and Pike 1970</td>
</tr>
<tr>
<td>Mount Stromlo</td>
<td>35° 18' S</td>
<td>—</td>
<td>0.63</td>
<td>0.25</td>
<td>0.54</td>
<td>Page 1964</td>
</tr>
<tr>
<td>Deniliquin</td>
<td>35° 52' S</td>
<td>0.49—0.78</td>
<td>—</td>
<td>0.27</td>
<td>0.54</td>
<td>De Vries 1958</td>
</tr>
<tr>
<td>Tunis</td>
<td>36° 51' N</td>
<td>—</td>
<td>—</td>
<td>0.16</td>
<td>0.59</td>
<td>Damagnez 1963</td>
</tr>
<tr>
<td>El Aquina</td>
<td>37° 0' N</td>
<td>—</td>
<td>—</td>
<td>0.28</td>
<td>0.43</td>
<td>Linacre 1967</td>
</tr>
<tr>
<td>Salt Lake City</td>
<td>40° 44' N</td>
<td>—</td>
<td>—</td>
<td>0.20°</td>
<td>0.47°</td>
<td>Chidley and Pike 1970</td>
</tr>
<tr>
<td>Ely</td>
<td>41° 0' N</td>
<td>0.61—0.89</td>
<td>0.77</td>
<td>0.54</td>
<td>0.18</td>
<td>Löf et al. 1966</td>
</tr>
<tr>
<td>Blue Hill</td>
<td>41° 30' N</td>
<td>0.42—0.60</td>
<td>0.52</td>
<td>0.22</td>
<td>0.50</td>
<td>Löf et al. 1966</td>
</tr>
<tr>
<td>Madison</td>
<td>43° 5' N</td>
<td>0.40—0.72</td>
<td>0.58</td>
<td>0.30</td>
<td>0.34</td>
<td>Löf et al. 1966</td>
</tr>
<tr>
<td>Nice</td>
<td>43° 40' N</td>
<td>0.49—0.76</td>
<td>0.61</td>
<td>0.17</td>
<td>0.63</td>
<td>Löf et al. 1966</td>
</tr>
<tr>
<td>Versailles</td>
<td>48° 48' N</td>
<td>—</td>
<td>0.42</td>
<td>0.23</td>
<td>0.50</td>
<td>Page 1964</td>
</tr>
<tr>
<td>Gemboux</td>
<td>50° 36' N</td>
<td>—</td>
<td>0.33</td>
<td>0.15</td>
<td>0.54</td>
<td>Page 1964</td>
</tr>
<tr>
<td>Kew</td>
<td>51° 30' N</td>
<td>0.17—0.46</td>
<td>0.33</td>
<td>0.14</td>
<td>0.66</td>
<td>Page 1964</td>
</tr>
<tr>
<td>Rothamsted</td>
<td>51° 48' N</td>
<td>—</td>
<td>0.36</td>
<td>0.18</td>
<td>0.55</td>
<td>Page 1964</td>
</tr>
<tr>
<td>Hamburg</td>
<td>53° 33' N</td>
<td>0.11—0.49</td>
<td>0.36</td>
<td>0.22</td>
<td>0.57</td>
<td>Löf et al. 1966</td>
</tr>
<tr>
<td>Stockholm</td>
<td>59° 32' N</td>
<td>—</td>
<td>0.22°</td>
<td>0.52°</td>
<td>Page 1964</td>
<td></td>
</tr>
<tr>
<td>Lerwick</td>
<td>60° 9' N</td>
<td>—</td>
<td>0.23°</td>
<td>0.56°</td>
<td>Linacre 1967</td>
<td></td>
</tr>
<tr>
<td>Fairbanks</td>
<td>64° 30' N</td>
<td>—</td>
<td>0.22</td>
<td>0.52</td>
<td>Linacre 1967</td>
<td></td>
</tr>
<tr>
<td>West Africa</td>
<td>10° 0' N</td>
<td>—</td>
<td>0.19</td>
<td>0.60</td>
<td>Davies 1965</td>
<td></td>
</tr>
<tr>
<td>Java</td>
<td>6° 30' S</td>
<td>—</td>
<td>0.29</td>
<td>0.29</td>
<td>Black et al. 1954</td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>12° 43' S</td>
<td>—</td>
<td>0.26</td>
<td>0.50</td>
<td>Linacre 1967</td>
<td></td>
</tr>
<tr>
<td>Central Africa</td>
<td>15° 0' S</td>
<td>—</td>
<td>0.32°</td>
<td>0.47°</td>
<td>Linacre 1967</td>
<td></td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>15° 30' N</td>
<td>—</td>
<td>0.36°</td>
<td>0.47°</td>
<td>Chidley and Pike 1970</td>
<td></td>
</tr>
<tr>
<td>Kimberley</td>
<td>16° 0' S</td>
<td>—</td>
<td>0.33°</td>
<td>0.43°</td>
<td>Linacre 1967</td>
<td></td>
</tr>
<tr>
<td>Jamaica</td>
<td>18° 0' N</td>
<td>—</td>
<td>0.31°</td>
<td>0.49°</td>
<td>Page 1964</td>
<td></td>
</tr>
<tr>
<td>East Mediterranean</td>
<td>25° 30' N</td>
<td>—</td>
<td>0.32°</td>
<td>0.47°</td>
<td>Chidley and Pike 1970</td>
<td></td>
</tr>
<tr>
<td>Wisconsin</td>
<td>43° 0' N</td>
<td>—</td>
<td>0.18°</td>
<td>0.55°</td>
<td>Linacre 1967</td>
<td></td>
</tr>
<tr>
<td>Canada</td>
<td>52° 0' N</td>
<td>—</td>
<td>0.25°</td>
<td>0.62°</td>
<td>Linacre 1967</td>
<td></td>
</tr>
<tr>
<td>Southern Scotland</td>
<td>55° 0' N</td>
<td>—</td>
<td>0.20°</td>
<td>0.51°</td>
<td>Nkedirim 1970</td>
<td></td>
</tr>
</tbody>
</table>

1°: Based on daily values of n/N, instead of monthly
2°: Based on values for unknown periods
Glover and McCulloch (1958) give:

\[ a = 0.29 \cos \varphi \]
\[ b = 0.52 \]

valid for \( 60^\circ N - 60^\circ S \), where \( \varphi \) = latitude (degrees).

The dependence of \( a \) on \( \varphi \) is due to the fact that the optical absolute air mass \( m \) decreases with decreasing latitude, so the transmittance of the atmosphere increases in the direction of the equator. Page (1964) has criticised the formula of Glover and McCulloch.

Penman (1956) gives:

\[ a = 0.18 \]
\[ b = 0.55 \]

These values have been found for England and Ghana and should be valid all over the world.

As follows from section 2.3.1, the above-mentioned formula cannot give accurate results at any particular station. More accurate values of the solar radiation reaching the earth's surface for specific stations can be calculated with \( a \)- and \( b \)-values for such stations.

2.3.2.3. Data

Table 5 gives a list of \( a \)-, \( b \)- and \( n/N \)-values, given by several authors. Baars (1970) has calculated the seasonal \( a \)- and \( b \)-values for four stations in Yugoslavia. These values are given in table 6.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( a )</td>
<td>( b )</td>
<td>( a )</td>
<td>( b )</td>
</tr>
<tr>
<td>Ljubljana</td>
<td>46° 4'</td>
<td>0.14</td>
<td>0.53</td>
<td>0.21</td>
<td>0.47</td>
</tr>
<tr>
<td>Beograd</td>
<td>44° 47'</td>
<td>—</td>
<td>—</td>
<td>0.26</td>
<td>0.49</td>
</tr>
<tr>
<td>Skopje</td>
<td>41° 59'</td>
<td>0.18</td>
<td>0.53</td>
<td>0.30</td>
<td>0.42</td>
</tr>
<tr>
<td>Ulcinj</td>
<td>41° 55'</td>
<td>—</td>
<td>—</td>
<td>0.35</td>
<td>0.43</td>
</tr>
</tbody>
</table>
Stokmans (1971) compiled the summer and winter $a$, $b$, and $n/N$-values for several European stations (see table 7).

Table 7: Summer and winter values of $a$, $b$, and $n/N$ (mean values) for 10 European stations (after Stokmans (1971))

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude (N)</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$a$</td>
<td>$b$</td>
</tr>
<tr>
<td>Vila Nova de Gaia (Portugal)</td>
<td>41° 8'</td>
<td>0.29</td>
<td>0.51</td>
</tr>
<tr>
<td>Macerata (Italy)</td>
<td>43° 17'</td>
<td>0.21</td>
<td>0.55</td>
</tr>
<tr>
<td>Modena (Italy)</td>
<td>44° 38'</td>
<td>0.40</td>
<td>0.35</td>
</tr>
<tr>
<td>Wageningen (the Netherlands)</td>
<td>51° 57'</td>
<td>0.21</td>
<td>0.54</td>
</tr>
<tr>
<td>Svalöv (Sweden)</td>
<td>55° 55'</td>
<td>0.25</td>
<td>0.50</td>
</tr>
<tr>
<td>Visby (Sweden)</td>
<td>57° 39'</td>
<td>0.24</td>
<td>0.57</td>
</tr>
<tr>
<td>Torslanda (Sweden)</td>
<td>57° 42'</td>
<td>0.21</td>
<td>0.55</td>
</tr>
<tr>
<td>Stockholm (Sweden)</td>
<td>59° 21'</td>
<td>0.21</td>
<td>0.57</td>
</tr>
<tr>
<td>Karlstad (Sweden)</td>
<td>59° 22'</td>
<td>0.25</td>
<td>0.58</td>
</tr>
<tr>
<td>Frösön (Sweden)</td>
<td>63° 12'</td>
<td>0.26</td>
<td>0.62</td>
</tr>
</tbody>
</table>

Löf, Duffie and Smith (1966) give a table of $a$, $b$, and $n/N$-values (see table 8), in which the $a$- and $b$-values are correlated with the climate and vegetation types. Climate and vegetation strongly influence the atmosphere and albedo. This seems to be a good way of giving $a$- and $b$-values of wide validity. The climate determination is based on Trewartha (1954) and (1961). Löf et al. base vegetation on Küchler's map (Goode's World Atlas, edited by Espenshade (1960)).

Some authors give other formulae than the Ångström type formula for estimating $R$ (see: Hinzpeter (1959)). However, they always need constants. The problem is that the constants are not given for many stations or large areas, unless very simplified and thus not accurate. Only the constants $a$ and $b$ are given for many stations and regions (tables 5, 6, and 7), and different climates and vegetations (table 8). The other formulae are therefore not considered.
Page announced in his paper (already referred to, see Page (1964)) a formula of the Ångström type with a reasonably sound climatological basis. The constants should be related to the latitude and the transmission characteristics of the atmosphere for any particular season of the year at any given locality. This implies that the constants must vary with the season. Such a formula goes in the direction followed by Löf, Duffie and Smith (table 8).

Table 8: a- and b-constants and sunshine-hour percentages correlated to climate and vegetation (Löf et al. (1966))

<table>
<thead>
<tr>
<th>Location</th>
<th>Climate</th>
<th>Vegetation</th>
<th>Sunshine hours in % of possible (100 n/N)</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charleston, S.C. (U.S.A.)</td>
<td>Cf</td>
<td>E</td>
<td>60—75</td>
<td>67</td>
<td>0.48</td>
</tr>
<tr>
<td>Atlanta, Ga. (U.S.A.)</td>
<td>Cf</td>
<td>M</td>
<td>45—71</td>
<td>59</td>
<td>0.38</td>
</tr>
<tr>
<td>Miami, Flo. (U.S.A.)</td>
<td>Aw</td>
<td>E-GD</td>
<td>56—71</td>
<td>65</td>
<td>0.42</td>
</tr>
<tr>
<td>Madison, Wis. (U.S.A.)</td>
<td>Df</td>
<td>M</td>
<td>40—72</td>
<td>58</td>
<td>0.30</td>
</tr>
<tr>
<td>El Paso, Tex. (U.S.A.)</td>
<td>BW</td>
<td>D Si</td>
<td>78—88</td>
<td>84</td>
<td>0.54</td>
</tr>
<tr>
<td>Poona (India)-monsoon</td>
<td>Am</td>
<td>S</td>
<td>25—49</td>
<td>37</td>
<td>0.30</td>
</tr>
<tr>
<td>Poona (India)-dry</td>
<td>Am</td>
<td>S</td>
<td>65—89</td>
<td>81</td>
<td>0.41</td>
</tr>
<tr>
<td>Albuquerque, N.M. (U.S.A.)</td>
<td>BS-BW</td>
<td>E</td>
<td>68—85</td>
<td>78</td>
<td>0.41</td>
</tr>
<tr>
<td>Malange (Angola)</td>
<td>Aw-BS</td>
<td>GD</td>
<td>41—84</td>
<td>58</td>
<td>0.34</td>
</tr>
<tr>
<td>Hamburg (Germany)</td>
<td>Cf</td>
<td>D</td>
<td>11—49</td>
<td>36</td>
<td>0.22</td>
</tr>
<tr>
<td>Ely, Nevada (U.S.A.)</td>
<td>BW</td>
<td>Bzi</td>
<td>61—89</td>
<td>77</td>
<td>0.54</td>
</tr>
<tr>
<td>Brownsville, Tex. (U.S.A.)</td>
<td>BS</td>
<td>GD-sp</td>
<td>47—80</td>
<td>62</td>
<td>0.35</td>
</tr>
<tr>
<td>Tamanrasset (Sahara)</td>
<td>BW</td>
<td>D Sp</td>
<td>76—88</td>
<td>83</td>
<td>0.30</td>
</tr>
<tr>
<td>Honolulu (Hawaii)</td>
<td>Al</td>
<td>G</td>
<td>57—77</td>
<td>65</td>
<td>0.14</td>
</tr>
<tr>
<td>Blue Hill, Mass. (U.S.A.)</td>
<td>Df</td>
<td>D</td>
<td>42—60</td>
<td>52</td>
<td>0.22</td>
</tr>
<tr>
<td>Buenos Aires (Argentina)</td>
<td>Cf</td>
<td>G</td>
<td>47—68</td>
<td>59</td>
<td>0.26</td>
</tr>
<tr>
<td>Nice (France)</td>
<td>Cs</td>
<td>SE</td>
<td>49—76</td>
<td>61</td>
<td>0.17</td>
</tr>
<tr>
<td>Darien (Manchuria)</td>
<td>Dw</td>
<td>D</td>
<td>55—81</td>
<td>67</td>
<td>0.36</td>
</tr>
<tr>
<td>Stanleyville (Congo)</td>
<td>Af</td>
<td>B</td>
<td>34—56</td>
<td>48</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Cf — Continental, continuously moist.  
Cs — Continental, dry season in summer.  
Df — Snow forest, continuously moist.  
Dw — Snow forest, dry season in winter.  
Aw — Tropical forest, dry season in winter.  
Am — Tropical forest, monsoon rains.  
Af — Tropical forest, continuously moist.  
B — Broadleaf evergreen.  
M — Mixed: broadleaf deciduous and needleleaf evergreen trees.  
BZ — Broadleaf evergreen, dwarf-shrub form.  
D — Broadleaf deciduous trees.  
DS — Broadleaf deciduous, shrub form.  
E — Needleleaf evergreen trees.  
G — Grass.  
GD — Grass and broadleaf deciduous trees.  
S — Semi-deciduous: broadleaf evergreen and broadleaf deciduous trees.
This might lead to a handy formula, widely applicable. It is a pity that no paper could be found giving the announced formula. Perhaps it has not been published (not yet?). Page announced it in 1961.

**Availability of n- and N-data**

a. The n/N-data given in tables 5 and 7.

b. Most weather stations give n-data, sometimes directly the n/N-data. In a number of cases, monthly and annual totals are plotted on maps of the country in question; and such maps can be made for many years.

c. The N-values can be found in: 'Tables of Sunrise, Sunset and Twilight', Supplement to the American Ephemeris 1946. This publication is obtainable from the Superintendent of Documents, U.S.A. Government Printing Office, Washington D.C. (for definition 1, see 2.3.1.1.)

d. Perrin de Brichambaut 1963) p. 254 gives the total N-values for the three decades of each month for the latitude range 0° - 60°N (for definition 4, see 2.3.1.1.).

2.3.3. METHOD C – AVERAGE AMOUNT OF SOLAR ENERGY REACHING THE EARTH'S SURFACE IS GIVEN DIRECTLY

### 2.3.3.1. Introduction

During the past decades more and more solar radiation data have been recorded. This has enabled solar radiation maps to be constructed. The first records were mainly used to derive formulae, especially of the Angström type. Then with sunshine data sufficient information became available for the construction of radiation maps. Later on the construction of maps became directly possible due to the availability of radiation records.

### 2.3.3.2. Data

I. Annual world maps

World maps of the mean annual global radiation have been given by Landsberg et al. (1965) and Budyko (1955 and 1963). The latest map given by Budyko is probably the most accurate. This map has been reproduced by Perrin de Brichambaut (1968) (see map 13).

II. Monthly world maps

World maps of mean monthly global radiation have been given by Budyko (1955) and Budyko (1963), Black (1956), Bernhardt and Philips (1958), Dov Ashbel (1961) and Löf, Duffie and Smith (1965).

Budyko in particular has used calculations. Black has used the radiation data from some 90 stations, together with calculations.

Ashbel has used the data from the International Geophysical Year only.

Löf, Duffie and Smith doubtlessly have given the most comprehensive maps (see map 14-25). They mapped global radiation data from 668 stations, scattered all over the world, whereas sunshine hours have been used in estimating radiation in another 233 locations (see map 26). These sunshine records generally cover long periods, i.e. 20 to 60 years. The authors applied the formula \( R = R_a (a + b \frac{n}{N}) \). Table 9 gives an idea of the duration of the radiation records used. Isolines of constant radiation have been drawn at intervals of 50 cal.cm. ² day⁻¹. All data have been standardized to the I.P.S. 1956.

30
Table 9: Duration of radiation records (Löf et al. (1966))

<table>
<thead>
<tr>
<th>Continent</th>
<th>10 or more</th>
<th>5 to 10</th>
<th>3 to 5</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>54</td>
<td>37</td>
<td>20</td>
<td>17</td>
<td>9</td>
</tr>
<tr>
<td>South America</td>
<td>1</td>
<td>2</td>
<td>24</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>Europe</td>
<td>19</td>
<td>38</td>
<td>125</td>
<td>26</td>
<td>11</td>
</tr>
<tr>
<td>Africa</td>
<td>0</td>
<td>21</td>
<td>31</td>
<td>13</td>
<td>6</td>
</tr>
<tr>
<td>Asia</td>
<td>16</td>
<td>16</td>
<td>84</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>Australia</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Antarctica</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Oceans and Islands</td>
<td>0</td>
<td>5</td>
<td>14</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

Only Antarctica is missing on the world map (70°S - 90°N). The publication by Löf et al. (1965) also gives tabulated global radiation data for Antarctica.

III. Monthly (seasonal) maps of countries and regions

Complete monthly or seasonal maps, which can give more detailed information than the world maps of Löf et al., are available for the following countries or regions (treated in alphabetical order).

a. Israel

Stanhill (1962) gives maps of the estimated average solar radiation distribution over Israel for each month of the year (see map 27-38). The maps give isolines at intervals of 25 cal.cm⁻².day⁻¹. The relationship between the amount of solar radiation measured and the observed amount of cloud cover (C') has been investigated using data from three stations in Israel, representing the main climatic regions. The following formula has been found:

\[ R = R_0 (0.7985 - 0.0389C' - 0.00013C'^2) \]

C' = mean monthly cloud cover on a scale of 9 (0 = cloudless sky, and 8 = completely overcast sky). Mean monthly values of cloud cover observed at 45 stations in Israel were used to prepare the maps.

b. Japan

Sekihara (1964) gives maps for the four seasons. Isolines are drawn at intervals of 20 cal.cm⁻².day⁻¹. The data are based on measurements by about 30 stations during an 8 year period.

c. Northern Europe

Black (1960) has constructed maps for Northern Europe, based on the measurements by 23 stations. The stations are located in an area bounded by latitudes 51°N and 61°N and longitudes 5°W and 30°W approximately. The maps concern the southern part of
Scandinavia, the Netherlands, a part of Belgium, the northern parts of Western Germany, Eastern Germany and Poland, and a part of the Soviet Union. They are based on measurements over many years. Isolines have been drawn at intervals of 25 cal.cm$^{-2}$ day$^{-1}$, or 12.5 cal.cm$^{-2}$.day$^{-1}$ (for winter); see maps 39-50.

d. North Pole Area
Gavrilova (1966) gives monthly maps of the monthly totals of global radiation in the Arctic (65°N - 90°N). The isolines have been drawn at 1 kcal.cm$^{-2}$ intervals in areas with a high isoline density at 2 kcal.cm$^{-2}$, intervals, and in months with a small influx at 0.5 kcal.cm$^{-2}$. The maps are based on records in 21 fixed land stations and 13 drifting stations. The measurements by the drifting stations were made for a year only, by the fixed land stations for some years and in some cases for longer periods.

e. United States of America
Bennett (1965) gives monthly maps of the mean daily insolation for the United States. The maps are based on 12 years of radiation records by 59 stations; for another 113 stations the amounts of global radiation have been estimated from sunshine records (see maps 51-62).

IV. Further information on global radiation, more detailed than the world maps of Löf et al.
The global radiation data from most recording stations are published. It would be going too far to deal with all known publications.
In this paragraph only those publications are mentioned — as far as known to the author — which concern countries or regions. These publications can give more detailed information than the existing world maps.

a. World information
The measured global radiation data from many stations (about 300) all over the world have been published since 1964 in the W.M.O. (monthly periodical) publication ‘Solar Radiation and Radiation Balance Data’. For most countries data are given on a few representative stations only.
(Solar Radiation and Radiation Balance Data. Publication of radiation data from all over the world under the auspices of W.M.O. (World Meteorological Organisation), by the Hydrometeorological Service, Leningrad. English and Russian.)

b. Africa
The measured global radiation data from many stations (about 70) all over Africa have been published in the ‘Quarterly Radiation Bulletin’, since 1954.

c. France
Perrin de Brichambaut (1968) gives maps for the months January, April, July and October. These maps give isolines at intervals of 200 joules.cm$^{-2}$.month$^{-1}$, (1 joule = 0.239 cal.). The maps show estimated values using sunshine data over a 14-year period.

d. The Indian Ocean
Mani et al. (1967) have constructed maps for the same four months January, April, July and October. The world maps by Löf et al. give more detailed information. However, the
maps by Mani et al. are more recent and give the solar radiation in areas where Löf et al. give only dotted lines.

The Indian Ocean is taken very widely: from 10°W to 160°W and from 50°N to 50°S. The isolines are given at intervals of 2 kcal.cm⁻².month⁻¹. The data are based on records of global radiation; sometimes over a number of years, sometimes over a few years.

Calculated values are also used.

c. Italy
Measured global radiation data have been plotted on maps for every month since July 1955. The first 12 maps (July 1955 - July 1956) have been published by De Pasquale (1956).

f. The Netherlands
Daily totals of the average global radiation at Wageningen (averaged over 1946-1953) are given by De Vries (1955). At present there is a radiation network in the Netherlands. Global radiation is measured at Beek, De Bilt, Den Helder, Eelde and Vlissingen. Results of these records (a publication) can be expected in the near future.

The monthly bulletin ‘Maandelijks overzicht der Weersgesteldheid’ of the K.N.M.I. (Koninklijk Nederlands Meteorologisch Instituut) at De Bilt gives the daily totals of measured values of R at Beek, De Bilt, Den Helder, Eelde and Vlissingen; since a few years. For De Bilt, the normal monthly values are also published.

g. North Pole Area
Vowinckel and Orvig (1964) give much information (maps and tabulated values) about the global radiation in the Arctic.

h. Portugal
The measured amounts of global radiation for each month from 1955 until now have been averaged and plotted on maps (see Portugal Serviço Meteorológico Nacional Boletim actinometrico de Portugal, Mimeo Lisbon, from 1955 up till now). In 1967 the R-values were given for 35 stations; for many stations also the deviations from the mean are given.

i. Soviet Union
Berlyand et al. (1955) and Pinovarova (1968) give monthly maps of the global radiation estimated for the Soviet Union. Perhaps these maps give more detailed information than those given by Löf et al. From these U.S.S.R. maps only the references are known to the present writer.

j. Western Africa
Perrin de Brichambaut (1968) has estimated the global radiation throughout Western Africa for the months January, April, July and October, as was done for France. However, in this case the estimates are based on a relatively small number of measurements only (in view of the areal distribution of the stations and the number of years of record).

k. United States of America
The United States Climatological Summaries print for each month a map of the deviations from the mean of the global radiation.
2.4. VARIATION IN $R_o$, $R_{cl}$ AND $R$ FROM YEAR TO YEAR

2.4.1. VARIATION IN $R_o$

The solar radiation at the top of the atmosphere varies within 1%, owing to the variation in the solar constant defined for the mean sun-earth distance. The variation in the solar constant due to the varying sun-earth distance is included in table 3 and amounts to a maximum of $+3.5\%$ or $-3.5\%$.

2.4.2. VARIATION IN $R_{cl}$

The solar radiation on clear days varies from year to year by about 5% owing to water vapour but more especially to dust. Owing to man-made air pollution in highly industrialized areas and in areas of much natural dust this variation may be even more. (De Boer (1966)).

2.4.3. VARIATION IN $R$

The following data may give an idea of the variation in $R$.

Stockholm. Extreme monthly totals (1941-1956) (Lindholm (1959))

<table>
<thead>
<tr>
<th>Month</th>
<th>1941</th>
<th>1942</th>
<th>1943</th>
<th>1944</th>
<th>1945</th>
<th>1946</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1202</td>
<td>11253</td>
<td>11253</td>
<td>11253</td>
<td>1202</td>
<td>11253</td>
</tr>
<tr>
<td>April</td>
<td>10764</td>
<td>10764</td>
<td>10764</td>
<td>10764</td>
<td>10764</td>
<td>10764</td>
</tr>
<tr>
<td>July</td>
<td>14490</td>
<td>14490</td>
<td>14490</td>
<td>14490</td>
<td>14490</td>
<td>14490</td>
</tr>
<tr>
<td>October</td>
<td>5977</td>
<td>5977</td>
<td>5977</td>
<td>5977</td>
<td>5977</td>
<td>5977</td>
</tr>
</tbody>
</table>

Wageningen. Extreme monthly totals (De Vries (1955))

<table>
<thead>
<tr>
<th>Month</th>
<th>1946</th>
<th>1947</th>
<th>1948</th>
<th>1949</th>
<th>1950</th>
<th>1951</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>4146</td>
<td>10764</td>
<td>14490</td>
<td>14490</td>
<td>14490</td>
<td>14490</td>
</tr>
<tr>
<td>April</td>
<td>10625</td>
<td>10625</td>
<td>10625</td>
<td>10625</td>
<td>10625</td>
<td>10625</td>
</tr>
<tr>
<td>July</td>
<td>11253</td>
<td>11253</td>
<td>11253</td>
<td>11253</td>
<td>11253</td>
<td>11253</td>
</tr>
<tr>
<td>October</td>
<td>980</td>
<td>980</td>
<td>980</td>
<td>980</td>
<td>980</td>
<td>980</td>
</tr>
</tbody>
</table>

Delhi, India. Extreme monthly totals (Venkiteswaran (1964))

<table>
<thead>
<tr>
<th>Month</th>
<th>1957</th>
<th>1958</th>
<th>1959</th>
</tr>
</thead>
<tbody>
<tr>
<td>July</td>
<td>15200</td>
<td>7590</td>
<td>7590</td>
</tr>
</tbody>
</table>

As may be clear, the variation in the amount of solar radiation reaching the earth's surface is highly dependent on the cloudiness. Some regions have fairly constant cloudiness from year to year, other regions have not. Stanhill (1962), for example, gives for Israel a variation in the monthly totals for each month from year to year within 10%.

2.5. ACCURACY

In fact, we want to know the accuracy, especially for monthly totals of:
1. actually measured values of $R$.
2. estimated values of $R$.
3. long-term mean values of $R$ averaged from measurements.
4. long-term mean values of $R$ averaged from estimations.
2.5.1. ACCURACY OF MEASURED VALUES OF R

The accuracy of measured values is, of course, dependent on the instrument used. It may be said that the absolute error in the monthly sums of measured radiation is generally less than 5%.

2.5.2. ACCURACY OF ESTIMATED VALUES OF R

The accuracy of the estimated values is highly dependent on the formula used. With the formulae of the Ångström type and given a and b or α and β for the station or small region in question, the monthly totals may be calculated within an error of 10-15%, especially when the α- and β- or a- and b-values are specified for the seasons or months of the year. If the same constants are used for large regions and especially if annual a- and b- or α- and β-values are used, the errors will increase to 20% and more.

2.5.3. ACCURACY OF MEAN VALUES OF R AVERAGED FROM MEASUREMENTS

The variation from year to year is not equal everywhere. Therefore, the number of years necessary to obtain a true long term mean varies from region to region, depending on the climate. Black (1964) shows that the number of years of record necessary to establish the true mean 5%, at 0.05 probability, varies from 3 to more than 30 years. In only a few cases measurements made over 30 years or longer are available. So, we may conclude that the accuracy of the given averages (the maps) sometimes amounts to more than 5% of the true means, and sometimes it is within 5%.

2.5.4. ACCURACY OF MEAN ESTIMATED AMOUNTS OF R

The accuracy of mean estimated amounts of R depends on the formula(e) used and on the accuracy and number of n-, C- or C'-measurements. It may be said that the absolute error of mean estimated amounts of R is generally within 10%, especially for small regions and if the n-, C- or C'-records of many years have been used.

2.6. CONCLUSIONS

Evaporation calculations are needed to predict the evaporation and to calculate the evaporation for a certain period in the past (for instance, to determine the water balance over a certain period).

2.6.1. PREDICTION

The possibilities of obtaining the desired global radiation data are:

a. The world maps of Löf et al. (1965) and the more detailed maps dealt with in 2.3.3.2. III and 2.3.3.2. IV.

b. Average values from one or more stations in the neighbourhood. As far as known, such values are published, in the countries: the Netherlands (see 2.3.3.2. IV f), Portugal (see 2.3.3.2. IV h), the U.S.A. (see 2.3.3.2. IV k), and also for many stations elsewhere.
2.6.2. CALCULATIONS CONCERNING THE PAST

There are the following possibilities of obtaining the desired global radiation data:

a. 'Solar Radiation and Radiation Balance Data' (see 2.3.3.2. IV a).

b. Actual measurements are also published for: Africa (see 2.3.3.2. IV b); Italy (periodical mentioned in Pasquale (1956)); the Netherlands (see 2.3.3.2. IV f); Portugal (see 2.3.3.2. IV h), and the U.S.A. (see 2.3.3.2. IV k).

c. Calculation with the aid of methods A or B (see 2.3.1. and 2.3.2.) and the measurements of n, C or C' for the period in question by a meteorological station in the vicinity.
3. Albedo

3.1. ALBEDO OF LAND SURFACES

In order to be able to compute the amount of absorbed global radiation, one should know the value of the albedo of the surface for global radiation. Kondratyev (1969), Budyko (1956) and Robinson (1966) show, among others, that the value of the albedo changes with the altitude of the sun. For the lower altitudes of the sun (in morning and evening hours), the albedo is usually considerably greater. The cause of this is the different reflective capacity of the rough underlying surfaces. The sun-rays are incident at different angles. At high sun altitudes the rays penetrate deeply into the surface and are absorbed there. At low sun altitudes the rays do not penetrate so much into the surface and a larger portion is reflected by the surface. Similarly, the albedo varies also with the season because of the varying height of the sun during the year. In summer the albedo is smaller, but in winter it is greater than the mean.

Table 10: The albedo of land, snow and ice surfaces for global radiation

<table>
<thead>
<tr>
<th>Type of surface</th>
<th>Albedo</th>
<th>Type of surface</th>
<th>Albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare soil</td>
<td></td>
<td>Fields, meadows, tundra</td>
<td></td>
</tr>
<tr>
<td>Dark soils</td>
<td>0.05—0.15</td>
<td>Rye and wheat fields</td>
<td>0.10—0.25</td>
</tr>
<tr>
<td>Moist grey soils</td>
<td>0.10—0.20</td>
<td>Potato plantations</td>
<td>0.15—0.25</td>
</tr>
<tr>
<td>Dry, clay or grey soils</td>
<td>0.20—0.35</td>
<td>Cotton plantations</td>
<td>0.20—0.25</td>
</tr>
<tr>
<td>Dry, light, sandy soils</td>
<td>0.25—0.45</td>
<td>Meadows</td>
<td>0.15—0.25</td>
</tr>
<tr>
<td>Snow and ice</td>
<td></td>
<td>Dry steppe</td>
<td>0.20—0.30</td>
</tr>
<tr>
<td>Fresh, dry snow</td>
<td>0.80—0.95</td>
<td>Tundra</td>
<td>0.15—0.20</td>
</tr>
<tr>
<td>Pure, white snow</td>
<td>0.60—0.70</td>
<td>Deciduous forests</td>
<td>0.15—0.20</td>
</tr>
<tr>
<td>Polluted snow</td>
<td>0.40—0.50</td>
<td>Coniferous forests</td>
<td>0.10—0.15</td>
</tr>
<tr>
<td>Sea ice</td>
<td>0.30—0.40</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 10 (after Budyko (1956)) gives a number of albedos for land, snow and ice surfaces. The lower values may be used for periods when the sun has high altitudes on average and at the low latitudes. The higher values may be used for periods when the sun has low altitudes on average and at the high latitudes. The variation of the albedo with the season and the latitudes is clearly given in Table 11 for the albedo of a water surface (see 3.2.).
3.2. ALBEDO OF A WATER SURFACE

The albedo of water surfaces is, on average, smaller than that of most of the land surfaces. The relatively great absorption of global radiation in water is explained by the fact that the sun's rays penetrate the upper water layers. There they are scattered and almost completely absorbed. This is why the albedo of muddy water is considerably greater.

Waves can have much influence on the albedo (see Robinson (1966)). However, for evaporation studies we consider monthly periods, in a few cases 10 days. For this reason it is mostly allowed to neglect the influence of waves on the albedo.

Table 11 (after Budyko (1956)) gives the albedo of a water surface as a function of latitude and month of the year. These data can also be used in calculations for the Southern Hemisphere, taking into account the proper changes of the seasons.

Table 11: Water surface albedo for global radiation

<table>
<thead>
<tr>
<th>Lat.</th>
<th>J</th>
<th>F</th>
<th>M</th>
<th>A</th>
<th>M</th>
<th>J</th>
<th>J</th>
<th>A</th>
<th>S</th>
<th>O</th>
<th>N</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>70°N</td>
<td>—</td>
<td>0.23</td>
<td>0.16</td>
<td>0.11</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.10</td>
<td>0.13</td>
<td>0.15</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>60°N</td>
<td>0.20</td>
<td>0.16</td>
<td>0.11</td>
<td>0.08</td>
<td>0.08</td>
<td>0.07</td>
<td>0.08</td>
<td>0.09</td>
<td>0.10</td>
<td>0.14</td>
<td>0.19</td>
<td>0.21</td>
</tr>
<tr>
<td>50°N</td>
<td>0.16</td>
<td>0.12</td>
<td>0.09</td>
<td>0.07</td>
<td>0.07</td>
<td>0.06</td>
<td>0.07</td>
<td>0.07</td>
<td>0.08</td>
<td>0.11</td>
<td>0.14</td>
<td>0.16</td>
</tr>
<tr>
<td>40°N</td>
<td>0.11</td>
<td>0.09</td>
<td>0.08</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.07</td>
<td>0.08</td>
<td>0.11</td>
<td>0.12</td>
<td>—</td>
</tr>
<tr>
<td>30°N</td>
<td>0.09</td>
<td>0.08</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.07</td>
<td>0.08</td>
<td>0.09</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>20°N</td>
<td>0.07</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.07</td>
<td>0.07</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>10°N</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.07</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>0°N</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
4. Effective outgoing long wave radiation from a horizontal surface at the earth \((R_B)\).

4.1. INTRODUCTION

The effective outgoing long wave radiation \(R_B\) is also called 'net long wave radiation'. \(R_B\) consists of the algebraic sum of the terrestrial radiation \(R_{B\uparrow}\) and the long wave radiation of the atmosphere \(R_{B\downarrow}\):

\[
R_B = R_{B\uparrow} - R_{B\downarrow}.
\]

\(R_B\) is defined to be positive when \(R_{B\uparrow} > R_{B\downarrow}\). \(R_B\) is mostly positive; \(R_B\) may be negative only over short periods, to which no attention is paid in this paper.

\(R_B\) radiation has wavelengths from 3 to 100 \(\mu\text{m}\). This range is much longer than the wavelength range of global radiation (0.3 to 3.0 \(\mu\text{m}\)). Some authors use 2.0, others 3.0 or 5.0 \(\mu\text{m}\) as the boundary between short and long wave radiation.

In recent years \(R_B\) has been measured at an increasing number of stations. However, most of these measurements have been made to compile the net radiation \(H\) from \(R\), \(R_{B\uparrow}\), and \(R_{B\downarrow}\), or to check calculations of \(R_B\). As far as is known, there are no (monthly) maps of \(R_B\) in existence.

In order to compile \(H\), \(R_B\) has mostly been calculated. In recent years \(H\) has been measured directly by an increasing number of stations (at the moment by about 200 stations).

4.2. TYPES OF FORMULAE USED FOR CALCULATING \(R_B\)

The radiation of a surface follows Stefan's law and is equal to

\[
s \varepsilon T^4, \text{ often expressed in cal.cm}^{-2}.\text{day}^{-1}.
\]

where: \(T\) = surface temperature (\(^\circ\text{K}\))

\(\varepsilon\) = Stefan-Boltzmann constant (cal.cm\(^{-2}\).day\(^{-1}\).\(^\circ\text{K}^{-4}\)).

\(s\) = coefficient which characterises the deviation of radiation of the given surface from that of a black body. For a black body, \(s\) is equal to 1.

Under clear sky conditions the long wave radiation of the earth's surface is:

\[
R_{B\uparrow} = s_e \varepsilon T^4 \text{ cal.cm}^{-2}.\text{day}^{-1}.
\]

where: \(s_e = s\) of the earth’s surface.
The long wave radiation of the atmosphere is also dependent on the humidity of the air:

\[ R_{el} = s_\lambda T_\lambda s' f(e) \text{ cal.cm}^{-2}\text{.day}^{-1}. \]

where: 
- \( T_\lambda \) = temperature of the air 
- \( s_\lambda \) = \( s \) of the atmosphere 
- \( e \) = water vapour pressure.

Hence, the effective outgoing radiation under cloudless sky conditions is:

\[ R_{Bel} = s_\lambda T_\lambda s' f(e) \text{ cal.cm}^{-2}\text{.day}^{-1}. \]

Various methods are used for calculating \( R_{el} \). In practice, empirical formulae are commonly applied. The formulae most frequently used are those given by Angström and by Brunt. These formulae will now be dealt with, first for a clear sky and then for a cloudy sky.

**Clear sky**

Angström (1924) gives the following empirical formula for \( R_{el} \) with a clear sky:

\[ R_{Bel} = s_\lambda T_\lambda (a + b 10^{-e}) \text{ cal.cm}^{-2}\text{.day}^{-1}. \]

where: \( a, b \) and \( c = \) constants.

\( e = \) water vapour pressure in mm Hg.

Many authors have derived the constants \( a, b \) and \( c \) from measurements, but some have computed the constants theoretically. Some constants are given in table 12.

**Table 12: Constants in Angström's formula (after Kondratyev 1969)**

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Station or country</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raman</td>
<td>1935</td>
<td>Poona (India)</td>
<td>0.23</td>
<td>0.28</td>
<td>0.033</td>
</tr>
<tr>
<td>Chumakova</td>
<td>1947</td>
<td>Karadag (U.S.S.R.)</td>
<td>0.200</td>
<td>0.181</td>
<td>0.030</td>
</tr>
<tr>
<td>Boltz, Falkenberg</td>
<td>1949</td>
<td>Eastern Germany</td>
<td>0.180</td>
<td>0.250</td>
<td>0.055</td>
</tr>
<tr>
<td>Knepple</td>
<td>1959</td>
<td>Western Germany (?)</td>
<td>0.21</td>
<td>0.174</td>
<td>0.024</td>
</tr>
</tbody>
</table>

The constants appear to be highly divergent. This can be ascribed to inadequate consideration of all physical factors influencing the long wave radiation, to differences in the measuring methods applied (including the accuracy of the instruments) and to differences in climate. The differences due to climate can be only relatively small because we consider \( R_{el} \). The values of Boltz and Falkenberg should be considered reliable because they have been derived from 1320 records (cloudless sky) using a modernised instrument.

The empirical formula for calculating \( R_{Bel} \) proposed by Brunt (1939) is:

\[ R_{Bel} = s_\lambda T_\lambda (a - \beta Ve) \text{ cal.cm}^{-2}\text{.day}^{-1}. \]

where \( a \) and \( \beta \) are empirical constants.
The constants in Brunt's formula, obtained by different authors, are as variable as those in Angström's formula. This can be seen from table 13.

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Station or country</th>
<th>(a)</th>
<th>(\beta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raman and Desay</td>
<td>1935</td>
<td>Poona (India)</td>
<td>0.53</td>
<td>0.061</td>
</tr>
<tr>
<td>Chumakova</td>
<td>1947</td>
<td>Karadag (U.S.S.R.)</td>
<td>0.376</td>
<td>0.043</td>
</tr>
<tr>
<td>Berlyand and Berlyand</td>
<td>1952</td>
<td>U.S.S.R.</td>
<td>0.39</td>
<td>0.058</td>
</tr>
<tr>
<td>De Coster and Schuepp</td>
<td>1957</td>
<td>Leopoldville (Congo)</td>
<td>0.355</td>
<td>0.055</td>
</tr>
<tr>
<td>Goss and Brooks</td>
<td>1957</td>
<td>U.S.A.</td>
<td>0.34</td>
<td>0.039</td>
</tr>
<tr>
<td>Marshunova</td>
<td>1961</td>
<td>Karadag (U.S.S.R.)</td>
<td>0.305-0.395</td>
<td>0.040-0.078</td>
</tr>
<tr>
<td>Monteith</td>
<td>1961</td>
<td>Great Britain</td>
<td>0.47</td>
<td>0.075</td>
</tr>
</tbody>
</table>

Instead of \(T^\dagger\), \(1/2 (T_{\text{max}} + T_{\text{min}})\), is sometimes used, in which \(T_{\text{max}}\) and \(T_{\text{min}}\) are the daily maximum and daily minimum air temperature (Jensen et al. (1970)).

The application of the Angström and Brunt formulae, with suitably determined coefficients, yields practically equal results (Kondratyev (1969)). However, Brunt's formula is preferred to Angström's because it contains only two parameters instead of three.

A third type is that given by Efimova (see Kondratyev (1969) p. 574 and 577). Efimova proposed for \(f(e)\):

\[
 f(e) = a_1 - b_1 e
\]

where: \(a_1\) and \(b_1\) are constants.

Some examples are given in section 4.3.

The empirical formulae were subsequently generalised by taking into account the non-blackness of the earth's surface (by \(s\)) and the sometimes sharp variation in the near surface temperature with height. This variation can be considered as a temperature 'jump'.

As a rule, the value \(R_{\text{sc}}\) (and, of course, also \(R_{\text{n}}\)) is determined from the temperature and humidity of the air at a height of 1.5 to 2.0 m. Therefore, because of the difference in temperature between the soil and the air, it is more accurate to correct for the temperature 'jump' by adding the term \(s(e)(T_{\text{max}} - T_{\text{min}})\) to the right-hand side.

\[
 R_{\text{sc}} = s(e) (T_{\text{max}} - T_{\text{min}})
\]

As

\[
 T_{\text{max}} - T_{\text{min}} = (T + T_{\text{soil}}) (T - T_{\text{soil}}) (T - T_{\text{soil}}) = \left( T + T_{\text{soil}} \right) (T - T_{\text{soil}}) \approx 4T_{\text{soil}} (T - T_{\text{soil}})
\]

the following form is also used:

\[
 R_{\text{sc}} = s(e) (T_{\text{soil}} + 4T_{\text{soil}} (T - T_{\text{soil}}))
\]

Cloudy sky

In reality, the sky is nearly always cloudy. The influence of cloudiness on the effective outgoing long wave radiation is great.
When using the empirical formulae for the calculation of $R_b$, it is general practice to introduce the influence of cloudiness with the help of the relationship:

$$R_b = R_{bcl} \left( a_2 + b_2 \frac{n}{N} \right)$$

where: $a_2$ and $b_2$ = constants.

$n$ = actual duration of sunshine
$N$ = maximum possible duration of sunshine for the same period.

or: $R_b = R_{bcl} \left( 1 - cC \right)$

where: $c$ = a constant

$C$ = degree of cloudiness, expressed in tenths.

Since the influence of cloudiness depends on the height and density of the clouds, which varies from station to station, the authors give different values for $a_2$, $b_2$ and $c$. Some authors replace the averaged $c$ by three different coefficients $c_l$, $c_m$ and $c_u$, which characterise the effect of clouds of the lower, middle and upper levels respectively. In this case the formula reads:

$$R_b = R_{bcl} \left\{ 1 - \left( c_l C_l + c_m C_m + c_u C_u \right) \right\}$$

where $C_l$, $C_m$ and $C_u$ are the respective values of the lower, middle and upper degrees of cloudiness. Table 14 gives a number of $c_l$, $c_m$ - and $c_u$ - values as a function of latitude and the warm or cold half-year.

### Table 14: Mean $c_l$, $c_m$ - and $c_u$ - values as a function of latitude and season (after Kondratyev (1969))

<table>
<thead>
<tr>
<th>Latitude, degrees</th>
<th>Half-year period</th>
<th>$c_l$</th>
<th>$c_m$</th>
<th>$c_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over 60</td>
<td>cold</td>
<td>0.90</td>
<td>0.77</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>warm</td>
<td>0.86</td>
<td>0.72</td>
<td>0.27</td>
</tr>
<tr>
<td>60—50</td>
<td>cold</td>
<td>0.86</td>
<td>0.74</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>warm</td>
<td>0.80</td>
<td>0.67</td>
<td>0.24</td>
</tr>
<tr>
<td>50—40</td>
<td>cold</td>
<td>0.82</td>
<td>0.69</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>warm</td>
<td>0.78</td>
<td>0.65</td>
<td>0.19</td>
</tr>
</tbody>
</table>

4.3. SOME EXAMPLES OF COMPLETE FORMULAE FOR CALCULATING $R_b$

OR $R_{bcl}$

Meaning of the symbols used:

$T_a$ = air temperature °K. This temperature is measured at a height of 1.5 to 2.0 m.

c = water vapour pressure of the air (mm Hg), also measured at a height of 1.5 to 2.0 m.

$n$ = actual duration of sunshine.

$N$ = maximum possible duration of sunshine for the same period.

$\sigma$ = Stefan-Boltzmann constant.
The authors give different values of $\varepsilon$. For example:

- **Budyko (1955):** $\varepsilon = 117.2 \times 10^{-9} \text{cal.cm}^{-2}.\text{day}^{-1}.\text{O.K}^{-4}$
- **Penman (1955):** $\varepsilon = 118.0 \times 10^{-9} \text{cal.cm}^{-2}.\text{day}^{-1}.\text{O.K}^{-4}$
- **Monteith (1961):** $\varepsilon = 117.0 \times 10^{-9} \text{cal.cm}^{-2}.\text{day}^{-1}.\text{O.K}^{-4}$
- **Perrin du Bricheamput (1968):** $\varepsilon = 117.0 \times 10^{-9} \text{cal.cm}^{-2}.\text{day}^{-1}.\text{O.K}^{-4}$
- **Jensen and Asslyng (1967):** $\varepsilon = 117.1 \times 10^{-9} \text{cal.cm}^{-2}.\text{day}^{-1}.\text{O.K}^{-4}$
- **Kondratyev (1969):** correct value: $\varepsilon = 119.0 \times 10^{-9} \text{cal.cm}^{-2}.\text{day}^{-1}.\text{O.K}^{-4}$
- **Commonly applied:** $\varepsilon = 117.5 \times 10^{-9} \text{cal.cm}^{-2}.\text{day}^{-1}.\text{O.K}^{-4}$

$s$ = the coefficient which characterizes the deviation of radiation from the given surface on the earth from that of a black body. $s$ varies from 0.85 to 1.00. Budyko has mostly used $s = 0.90$.

c = coefficient. Budyko (1956) has provided c in a table as a function of latitude.
C = degree of cloudiness, expressed in tenths.
T = temperature of the earth's surface (°K).

These formulae are mostly used for the calculation of monthly totals. Therefore monthly means of $T_a$, $T$, $e$, $n$, $N$ and $C$ are used.

**I. A formula of the Ångström type**

a. \[ R_{\text{AD}} = s T_a (0.180 + 0.250 \times 10^{-0.035r}) \text{cal.cm}^{-2}.\text{day}^{-1} \]


**II. Formulae of the Brunt type**

b. \[ R_B = s T_a \left( 0.47 - 0.071 \frac{\gamma}{e} \right) (0.2 + 0.8 \frac{n}{N}) \text{cal.cm}^{-2}.\text{day}^{-1} \]

d. \[ R_B = s T_a \left( 0.39 - 0.058 \frac{\gamma}{e} \right) (1 - cC) + 4s T_a (T - T_a) \text{cal.cm}^{-2}.\text{day}^{-1} \]

(after Budyko (1955)).

e. \[ R_B = s T_a \left( 0.39 - 0.0096 \frac{\gamma}{e} \right) (1 - cC) \]

(after Budyko (1963)).

Monteith has compiled his formula from measurements taken in the British Isles.

**III. Formulae of the Efimova type**

f. \[ R_B = s T_a \left( 0.39 - 0.0178 \frac{\gamma}{e} \right) (1 - cC) + 4s T_a (T - T_a) \text{cal.cm}^{-2}.\text{day}^{-1} \]


Efimova proposed: $s = 0.95$.

g. \[ R_B = s T_a \left( 0.254 - 0.0066 \frac{\gamma}{e} \right) (1 - cC) \]

according to Efimova.

This formula has been computed for the U.S.S.R. from the International Geophysical Year measurements.

h. \[ R_B = s T_a \left( 0.39 - 0.0096 \frac{\gamma}{e} \right) (1 - cC) + 4s T_a (T - T_a) \text{cal.cm}^{-2}.\text{day}^{-1} \]

(after Budyko (1963)).

$c$ is provided in a revised table - see table 15 (revised with regard to the table for $c$ given by Budyko in 1955).

**Table 15:** The constant $c$ of Budyko's formula (1963) as a function of latitude (degrees)

<table>
<thead>
<tr>
<th>Lat.</th>
<th>5°</th>
<th>10°</th>
<th>15°</th>
<th>20°</th>
<th>30°</th>
<th>40°</th>
<th>50°</th>
<th>60°</th>
<th>70°</th>
<th>80°</th>
<th>85°</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$</td>
<td>0.50</td>
<td>0.52</td>
<td>0.55</td>
<td>0.59</td>
<td>0.63</td>
<td>0.68</td>
<td>0.72</td>
<td>0.76</td>
<td>0.80</td>
<td>0.84</td>
<td>0.86</td>
</tr>
</tbody>
</table>
4.4. ACCURACY OF $R_b$

The inaccuracy of monthly values of $R_b$, calculated with the recent formulae by a few investigators, was up to 25% of the observed values (see Jensen and Aslyng (1967) and Kondratyev (1969)).

The most reliable instruments for measuring $R_b$ still have inaccuracies of up to 10 to 15% (Kondratyev (1969)).

Thus, it is evident that it is not possible to calculate or measure $R_b$ values as accurately as $R$ values.

4.5. CONCLUSIONS WITH REGARD TO $R_b$

To obtain $R_b$-values, one has mostly to compute them. $R_b$ is measured by only relatively few stations, mostly not regularly. Data on $T_a$, $h$, $n$ or $c$ are available at many weather stations. $e$ can be computed from $h = e/e_a$, where $h$ is the relative humidity and $e_a$ is the saturation vapour pressure. Sometimes soil temperatures ($T$) are also available.

The constants of the $R_b$-formulae are, in fact, only valid for the location or country for which they have been compiled, owing to differences in climate. However, the inaccuracy of the calculated $R_b$-values, due to the inaccuracy of the constants, is mostly greater than the variations due to the climate (except for extreme climates). As shown by Kondratyev (1969) and Monteith (1961), fairly reliable $R_b$ formulae can be given for the following countries:

**Eastern Germany**

Angström type formula:

$$R_b = e T_a (0.180 + 0.250 \times 10^{-0.055e}) (1 - cC) \text{ cal.cm}^{-2}.\text{day}^{-1}.$$  
$c$ can be obtained from Budyko's table (table 15).

**Great Britain**

Brunt's type formula (see 4.3.g).

The same formula with the same constants has been used by Jensen and Aslyng (1967) for Copenhagen. The only difference is that Jensen and Aslyng defined $N$ as the sum of hours between sunrise and sunset minus one hour daily.

**Soviet Union**

Efimova's type formula (see 4.3.g).

The constant $c$ can be obtained from Budyko's table (table 15).

In order to gain some insight into the $R_b$-formulae, which are proposed to be valid all over the world, some of them have been compared. As the authors introduced the cloudiness in different ways and the correction term $4s e T_a^2 (T - T_a)$ only forms a small part (maximum about 10% of $R_{bd}$), the formulae have been compared only for clear-sky conditions (see table 16). The results of the 'Budyko 1963' formula (see 4.3.h) have turned out to be about the average of the other formulae, except at higher temperatures and water-vapour pressures. However, under such conditions the influence of the correction term and cloudiness increases. The different influence of cloudiness at differ-
ent climates has been included by Budyko by giving a table for \( c \) as a function of latitude (see table 15).

For these reasons, the 'Budyko 1963' formula can be recommended for calculating \( R_b \) when no formulae are available for the location (see tables 12 and 13) or country concerned (see above).

It will be clear that more accurate results will be obtained if \( c_l, c_m \) and \( c_u \) (provided in table 14) are used. However, in that case the sparsely available data \( C_l, C_m \) and \( C_u \) are needed.

**Remark**

Some authors, for example Swinbank (1963) and Anderson and Baker (1967) give formulae for computing \( R_{b'} \) under clear-sky conditions. In this way it is also possible to compile \( R_b \), when \( R_{b'} \) with a clear sky is computed (by accepting a value for the coefficient \( s \) of the surface) and when the influence of cloudiness is taken into account.
Table 16: Comparison of some formulae for net long wave radiation under clear-sky conditions (correction terms have been ignored)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>25%</td>
<td>1.14</td>
<td>253</td>
<td>192</td>
<td>304</td>
<td>228</td>
<td>222</td>
</tr>
<tr>
<td>0</td>
<td>50%</td>
<td>2.29</td>
<td>231</td>
<td>177</td>
<td>278</td>
<td>216</td>
<td>215</td>
</tr>
<tr>
<td>0</td>
<td>75%</td>
<td>3.44</td>
<td>213</td>
<td>166</td>
<td>258</td>
<td>203</td>
<td>209</td>
</tr>
<tr>
<td>0</td>
<td>100%</td>
<td>4.58</td>
<td>199</td>
<td>156</td>
<td>241</td>
<td>192</td>
<td>202</td>
</tr>
<tr>
<td>5</td>
<td>25%</td>
<td>1.63</td>
<td>261</td>
<td>199</td>
<td>314</td>
<td>240</td>
<td>235</td>
</tr>
<tr>
<td>5</td>
<td>50%</td>
<td>3.27</td>
<td>232</td>
<td>180</td>
<td>280</td>
<td>220</td>
<td>225</td>
</tr>
<tr>
<td>5</td>
<td>75%</td>
<td>4.90</td>
<td>210</td>
<td>165</td>
<td>254</td>
<td>201</td>
<td>215</td>
</tr>
<tr>
<td>5</td>
<td>100%</td>
<td>6.54</td>
<td>191</td>
<td>152</td>
<td>232</td>
<td>181</td>
<td>205</td>
</tr>
<tr>
<td>10</td>
<td>25%</td>
<td>2.30</td>
<td>266</td>
<td>204</td>
<td>321</td>
<td>249</td>
<td>248</td>
</tr>
<tr>
<td>10</td>
<td>50%</td>
<td>4.60</td>
<td>230</td>
<td>180</td>
<td>278</td>
<td>220</td>
<td>234</td>
</tr>
<tr>
<td>10</td>
<td>75%</td>
<td>6.90</td>
<td>202</td>
<td>161</td>
<td>245</td>
<td>190</td>
<td>219</td>
</tr>
<tr>
<td>10</td>
<td>100%</td>
<td>9.20</td>
<td>178</td>
<td>145</td>
<td>217</td>
<td>162</td>
<td>203</td>
</tr>
<tr>
<td>15</td>
<td>25%</td>
<td>3.19</td>
<td>268</td>
<td>208</td>
<td>324</td>
<td>255</td>
<td>261</td>
</tr>
<tr>
<td>15</td>
<td>50%</td>
<td>6.39</td>
<td>222</td>
<td>177</td>
<td>270</td>
<td>211</td>
<td>238</td>
</tr>
<tr>
<td>15</td>
<td>75%</td>
<td>9.58</td>
<td>187</td>
<td>153</td>
<td>228</td>
<td>167</td>
<td>216</td>
</tr>
<tr>
<td>15</td>
<td>100%</td>
<td>12.78</td>
<td>157</td>
<td>133</td>
<td>193</td>
<td>123</td>
<td>194</td>
</tr>
<tr>
<td>20</td>
<td>25%</td>
<td>4.38</td>
<td>267</td>
<td>209</td>
<td>323</td>
<td>253</td>
<td>270</td>
</tr>
<tr>
<td>20</td>
<td>50%</td>
<td>8.76</td>
<td>209</td>
<td>170</td>
<td>255</td>
<td>192</td>
<td>238</td>
</tr>
<tr>
<td>20</td>
<td>75%</td>
<td>13.15</td>
<td>165</td>
<td>140</td>
<td>203</td>
<td>131</td>
<td>206</td>
</tr>
<tr>
<td>20</td>
<td>100%</td>
<td>17.53</td>
<td>128</td>
<td>114</td>
<td>159</td>
<td>70</td>
<td>174</td>
</tr>
<tr>
<td>25</td>
<td>25%</td>
<td>5.94</td>
<td>261</td>
<td>207</td>
<td>317</td>
<td>249</td>
<td>276</td>
</tr>
<tr>
<td>25</td>
<td>50%</td>
<td>11.87</td>
<td>189</td>
<td>158</td>
<td>233</td>
<td>156</td>
<td>230</td>
</tr>
<tr>
<td>25</td>
<td>75%</td>
<td>17.81</td>
<td>134</td>
<td>121</td>
<td>168</td>
<td>163</td>
<td>184</td>
</tr>
<tr>
<td>25</td>
<td>100%</td>
<td>23.75</td>
<td>88</td>
<td>89</td>
<td>113</td>
<td>—30</td>
<td>137</td>
</tr>
<tr>
<td>30</td>
<td>25%</td>
<td>7.95</td>
<td>250</td>
<td>201</td>
<td>305</td>
<td>232</td>
<td>278</td>
</tr>
<tr>
<td>30</td>
<td>50%</td>
<td>15.91</td>
<td>161</td>
<td>141</td>
<td>200</td>
<td>99</td>
<td>210</td>
</tr>
<tr>
<td>30</td>
<td>75%</td>
<td>23.86</td>
<td>93</td>
<td>95</td>
<td>120</td>
<td>—37</td>
<td>142</td>
</tr>
<tr>
<td>30</td>
<td>100%</td>
<td>31.82</td>
<td>35</td>
<td>56</td>
<td>52</td>
<td>—170</td>
<td>73</td>
</tr>
</tbody>
</table>

1 Lecture notes by Prof. ir. A. Volker (see section 4.3.11.b).
5. Net radiation received by a horizontal surface at the earth

Chapters 2, 3 and 4 give the possibility of compiling the global radiation $R$, albedo $r$, and net long-wave radiation $R_b$ respectively. $H$ can be computed with the formula:

$$H = R (1 - r) - R_b$$

However, there is the possibility of obtaining rough $H$-values directly. The ‘Atlas of the Heat Balance of the Earth’, edited by M. I. Budyko (1963), gives monthly world maps of computed $H$-values. Isolines are given at intervals of 2 kcal.cm$^{-2}$.month$^{-1}$. These maps are approximate and, as shown by Terjung (1969), deviations of up to 40 percent with respect to data known to Terjung occur. For these reasons no copy of the monthly world maps of $H$ has been included in this paper. In all probability, $H$ can be computed more accurately from the data given in chapters 2, 3 and 4. For example, the $R$-values given by Löf et al. (1965) (see maps 14-25) are in general more accurate than the values used by Budyko. For a certain location or region, $r$ can be compiled more accurately than by simply using average values over a large area, as was probably used by Budyko. So using Budyko’s formula for computing $R_b$, it is possible to compute $H$, for a certain location or region more accurately than has been done by Budyko himself. However, for approximate information and orientation Budyko’s atlas remains very useful.

As far as is known maps of net radiation $H$ for a region or a country exist only in a few cases. Berlyand and Efimova (1955) give monthly maps of net radiation for the U.S.S.R., Mani et al. (1967), give maps of net radiation for the months January, April, July and October for the Indian Ocean and its wide surroundings. Pivonarova (1968) has compiled monthly maps of net radiation for the U.S.S.R., based on measurements during the International Quiet Sun Years.

$H$ is measured at several stations, mostly irregularly. In the monthly publication ‘Solar Radiation and Radiation Balance Data’ (see 2.3.3.2. IVa) the regular $H$-measurements by about 50 stations all over the world are published. It is a pity that the underlying surface is not mentioned. $R$ and $R_b$ may be constant, but if $r$ varies $H$ will also vary. This makes it difficult to use the data for surfaces in the neighbourhood with other $r$-values than the surface of the station in question.

Summarizing, $H$-values can be obtained in the following ways:

a. from measurements of a station in the neighbourhood.

b. from ‘Solar Radiation and Radiation Balance Data’ (see 2.3.3.2. IVa).

c. computation from the data given in chapters 2, 3 and 4.

d. from maps:


This atlas gives monthly world maps of $H$. The information is only approximate.

2. for the U.S.S.R.: the monthly maps of Berlyand and Efimova (1955) and those of
Pivonarova (1968). From these U.S.S.R. maps only the references are known to the present writer.

3. for the region of the Indian Ocean and wide surroundings: the maps of four months, given by Mani et al. (1967).

4. for the North-Pole Area, Gavrilova (1966) gives monthly maps of H.

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BAARS C., Verband tussen totale globale straling, relatieve zonneschijnduur en bewolkingsgraad (Draft Edition, Agricultural University, Wageningen, the Netherlands) 1970.


BRUNT D., Physical and Dynamical Meteorology, Cambridge University Press, 1939.


* A. für M.G. und B.B. means:
Archiv für Meteorologie, Geophysik und Bioklimatologie, Serie B.
Q.J. of the R.M.S. means:
Quarterly Journal of the Royal Meteorological Society.


PENMAN H. L., Natural Evaporation from Open Water, Bare Soil and Grass, Proceedings, Royal Society of London, Series A, vol. 93, 1948, p. 120.


STOKMANS J. A., The empirical relation between global radiation and duration of sunshine for several European meteorological stations, Agricultural University, Wageningen, the Netherlands (Draft edition), March 1971.


VRIES D. A. DE, Solar Radiation at Wageningen, Mededelingen Landbouwhogeschool, Wageningen, the Netherlands, 55 (6), 1955, p. 277.


REMARKS

An excellent review of literature (textbooks and periodicals) is given by Perrin de Brichambaut (1968). Of course, this could not include the important textbook of Kondratyev, published in 1969.
Map 1 - 12

Canada

(after Mateer (1955a))

Monthly $R_{cl}$-values (1 langley = 1 cal.cm.$^{-2}$).
AVERAGE CLOUDLESS DAY INSOLATION IN LANGLEYS
April 15
- Observed - Computed

AVERAGE CLOUDLESS DAY INSOLATION IN LANGLEYS
May 15
- Observed - Computed
AVERAGE CLOUDLESS DAY INSOLATION IN LANGLEYS

August 15
• Observed  • Computed

September 15
• Observed  • Computed
AVERAGE CLOUDLESS DAY INSOLATION IN LANGLEYS

October 15

- Observed - Computed

AVERAGE CLOUDLESS DAY INSOLATION IN LANGLEYS

November 15

- Observed - Computed
Map 13

World

(after Perrin de Brichambaut (1968))

Annual R-values (1 joule = 0.239 cal.).
Map 14 - 25

World

(after Löf et al. (1965)).

Monthly R-values.
Daily means of total solar radiation (direct + diffuse) incident on a horizontal surface in cal.cm^-2.day^-1

JANUARY
FEBRUARY

Daily means of total solar radiation (direct + diffuse)
Incident on a horizontal surface in cal. cm⁻²·day⁻¹
MARCH

Daily means of total solar radiation (direct + diffuse) incident on a horizontal surface in cal cm$^{-2}$ day$^{-1}$.
MAY

Daily means of total solar radiation (direct + diffuse) Incident on a horizontal surface in cal. cm\(^{-2}\) day\(^{-1}\)
Daily means of total solar radiation (direct + diffuse) incident on a horizontal surface in cal. cm$^{-2}$ day$^{-1}$
JULY

Daily means of total solar radiation (direct + diffuse)
Incident on a horizontal surface in cal.cm⁻² day⁻¹
AUGUST

Daily means of total solar radiation (direct + diffuse) incident on a horizontal surface in cal. cm$^2$. day$^{-1}$
SEPTEMBER

Daily means of total solar radiation (direct + diffuse)
Incident on a horizontal surface in cal.cm\(^{-2}\).day\(^{-1}\)
OCTOBER

Daily means of total solar radiation (direct + diffuse) Incident on a horizontal surface in cal. cm$^{-2}$ day$^{-1}$
NOVEMBER

Daily means of total solar radiation (direct + diffuse)
Incident on a horizontal surface in cal cm\(^{-2}\) day\(^{-1}\)
Daily means of total solar radiation (direct+diffuse) Incident on a horizontal surface in cal. cm$^{-2}$ day$^{-1}$
Map 26

World

(after Löf et al. (1966)).

Global radiation and sunshine-recording stations.
Israel

(after Stanhill (1962)).

Monthly R-values.
Figure 4
Monthly mean solar radiation on surface, January, February, March. g cals. cm² day

Figure 5
Monthly mean solar radiation on surface, April, May, June. g cals. cm² day

Figure 6
Monthly mean solar radiation on surface, July, August, September. g cals. cm² day

Figure 7
Monthly mean solar radiation on surface, October, November, December. g cals. cm² day
Map 39 - 50

Northern Europe

(after Black (1960)).

Monthly R-values.
United States of America

(after Bennett (1965)).

Monthly R-values (cal.cm⁻².day⁻¹).
NEAR DAILY INSOLATION IN LANGLEYS
UNITED STATES - MARCH, 1930-42
BASED EXCLUSIVELY ON ACTUAL DATA
BASED ON ACTUAL DATA AND ESTIMATED DATA FOR MONTHS WITH NO ACTUAL DATA
BASED EXCLUSIVELY ON ESTIMATED DATA
BASED WHOLLY ON ESTIMATED DATA
MARCH WEATHER DATA

NEAR DAILY INSOLATION IN LANGLEYS
UNITED STATES - APRIL, 1930-42
BASED EXCLUSIVELY ON ACTUAL DATA
BASED ON ACTUAL DATA AND ESTIMATED DATA FOR MONTHS WITH NO ACTUAL DATA
BASED EXCLUSIVELY ON ESTIMATED DATA
BASED WHOLLY ON ESTIMATED DATA
MARCH WEATHER DATA