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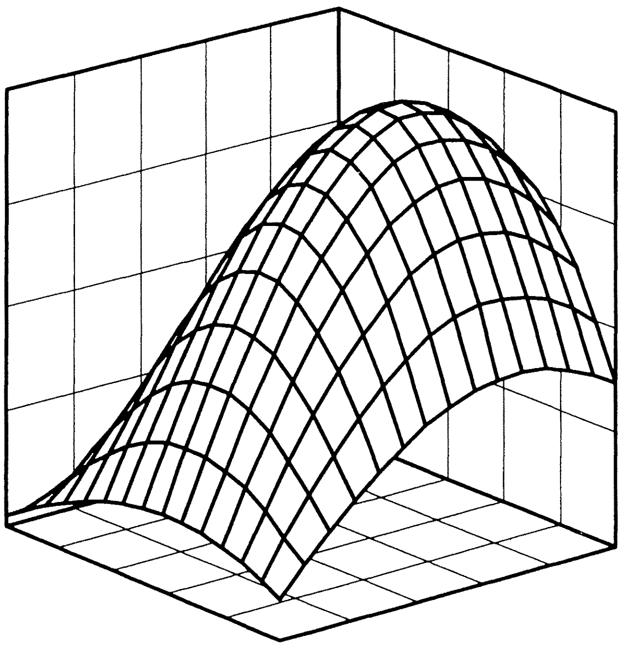
Implementation of the algorithms from Penman, Makkink and Priestley-Taylor



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Implementation of the algorithms from Penman, Makkink and Priestley-Taylor

D.W.G. van Kraalingen & W. Stol

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H. Terburg
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P.O. Box 14
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Phone: (+) 31 317.475723
Fax: (+) 31 317.423110
E-mail: h.terburg@ab.dlo.nl

Th.H. Jetten
Secretariat C.T. de Wit Graduate School
for Production Ecology
Lawickse Allee 13
NL-6701 AN Wageningen
Phone: (+) 31 317.485116
Fax: (+) 31 317.484855
E-mail: theo.jetten@beleid.spp.wau.nl

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List of Symbols

Symbol	Abbreviation	Meaning	Unit
a	RF	Reflection coefficient of the surface (= albedo)	-
α	DATMTR	Daily average atmospheric transmission coefficient	-
A_a	ANGA	A coefficient of Ångström formula	-
A_b	ANGB	B coefficient of Ångström formula	-
B_c		Coefficient of Brunt formula	-
B_d		Coefficient of Brunt formula	-
C_{MK}	MAKFAC	Makkink correction coefficient	-
C_{PT}	PTFAC	Priestley-Taylor correction coefficient	-
d		Displacement height	m
E		Rate of evaporation	mm d^{-1}
ε		Emissivity coefficient	-
e_2	VP	Vapour pressure at 2 m above the surface	kPa
E_a	EA	Isothermal evaporation	mm d^{-1}
E_{MK}		Makkink evapotranspiration	mm d^{-1}
E_{PM}		Penman evapotranspiration	mm d^{-1}
E_{PT}		Priestley-Taylor evapotranspiration	mm d^{-1}
$e_s(\mathrm{T})$	VPS	Saturated vapour pressure at temperature T	kPa
$f(u_2)$	FU2	Wind function	mm water d^{-1} kPa^{-1}
G		Flux of heat into the ground, soil or water	J m^{-2} d^{-1}
γ	PSCH	Psychrometer constant	kPa $°C^{-1}$
g		Conversion factor	kg m^{-3} Pa^{-1}
H		Sensible heat flux into the air	J m^{-2} d^{-1}
λ	LHVAP	Latent heat of evaporation of water	J g^{-1}
λE		Latent heat flux into the air	J.m^{-2} d^{-1}
λE_a		Isothermal latent heat flux	J.m^{-2} d^{-1}
λE_d		Air driven component of λE	J.m^{-2} d^{-1}
λE_r		Radiation driven component of λE	J.m^{-2} d^{-1}
n		Actual duration of sunshine	h d^{-1}
N		Maximum duration of sunshine	h d^{-1}
p		Coefficient of cloudiness factor	-
r	RE	Resistance to vapour transfer	s m^{-1}
R	RGBL	Universal gas constant	J $°C^{-1}$ mol^{-1}
ρc_p	RHOCP	Specific heat of air	J m^{-3} $°C^{-1}$
$R_{l,down}$	RDLI	Downward flux of long-wave radiation from the sky	J m^{-2} d^{-1}
$R_{l,up}$	RDLO	Upward flux of long-wave radiation from the earth	J m^{-2} d^{-1}
R_n	RDN	Net radiation	J m^{-2} d^{-1}
$R_{n,l}$		Net long-wave radiation	J m^{-2} d^{-1}
R_s	RDD	Downward flux of short-wave radiation	J m^{-2} d^{-1}
s	VPSL	Slope of saturated vapour pressure curve	kPa $°C^{-1}$
σ	SIGMA	Stefan Boltzmann coefficient	J m^{-2} d^{-1} $°K^{-4}$
T_2	TMDA	Average air temperature at 2 m above the surface	° C
T_s		Surface temperature of soil, crop or water	° C
u_2	WN	Wind speed at 2 m above the surface	m s^{-1}
VPD	VPD	Vapour pressure deficit	kPa
z_0		Roughness length	m

1. Objective and summary

Calculation of evapotranspiration is essential for the estimation of crop water use or for studying the effect of drought stress on crop performance with simulation models. Several methods are available for calculation of evapotranspiration. This report describes three different methods: the Penman method (1948) and the approaches of Makkink (1957) and Priestley-Taylor (1972). The modules described in this report are developed for use in general crop growth models for water-limited conditions, such as in Van Laar *et al.* (1992). The application of the modules, however, is not limited to the SUCROS type models.

The Penman method is important for the general understanding of evapotranspiration from surfaces both in more advanced models (such as greenhouse models) and in more simple approaches. When considered over longer periods of time (> 10 days), the Penman method calculates crop water loss with a reasonable degree of accuracy. It can be considered the best among the simple approaches. All three methods have in common that they estimate evapotranspiration of short, well-watered crops, however, they differ in their data requirements. Makkink and Priestley-Taylor require fewer meteorological observations because they are based on the observation that in many climates, the radiation-driven part of evapotranspiration is much more important than the part driven by vapour pressure deficit and wind speed. In the Priestley-Taylor equation, evapotranspiration is proportional to net radiation, while Makkink evapotranspiration is proportional to short-wave radiation. The Penman method requires daily values of radiation, temperature, vapour pressure and wind speed. The Makkink and Priestley-Taylor equations require only radiation and temperature.

The Priestley-Taylor equation is used world-wide, e.g. in the IBSNAT network, but regional calibration can be necessary since it is based on the assumption that a constant relation exists between the evaporative demand by radiation and by wind. The same holds for the Makkink equation which is calibrated for use during the growing season in The Netherlands. In The Netherlands, Makkink and Priestley-Taylor should be used only during the growing season. An important finding is that the Makkink and Priestley-Tailor methods are valid for a larger part of the year in areas closer to the equator. This more or less justifies the use of these simple methods in agro-ecological zonation studies in these areas.

The Penman formula calculates evapotranspiration by assuming that the surface temperature is not very different from the air temperature. Under normal circumstances this is indeed the case, but under extreme conditions surface temperatures can differ much from air temperatures, resulting in unwanted errors. To avoid this situation, the Penman module, as described here, can iteratively search for the equilibrium surface temperature and give an improved estimate of surface water loss.

2. Scientific descriptions

2.1. Penman method

2.1.1. Energy balance principle

The combination equation of Penman can be derived from the energy balance equation for an extensive area of open water, wet soil or crop as given in equation (2.1).

$$R_n - G - \lambda E - H = 0 \tag{2.1}$$

This equation simply states that the net radiation intercepted by the crop, water or soil surface (R_n) equals the energy lost by heat storage in the crop, water or soil (G, heat storage in the crop is too small to be considered here), plus the energy lost through evaporation (λE = latent heat of evaporation of water, λ multiplied by rate of evaporation E), plus the energy lost or gained through convection of sensible heat by the air (H). The direction of the sensible heat flux (H) is dependent on the sign of the temperature difference between the air and the surface under study. If the surface temperature (T_s) is lower than the air temperature (T_2), additional energy is transferred to the surface (as sensible heat). If the surface is warmer than the surrounding air the direction of the energy flux is the other way. When we consider that over longer periods of time the net energy flux into the ground (G) is zero, equation (2.1) simplifies to:

$$R_n - \lambda E - H = 0 \tag{2.2}$$

All terms of equation (2.2) are in some way dependent on the surface temperature (T_s) Given the environmental conditions such as radiation, air temperature, wind speed and vapour pressure, there is only one surface temperature for which equation (2.2) holds. The rate of evaporation then simply equals: R_n - H.

The latent heat flux basically is driven by the difference in vapour pressure between the surface and the environment. If the surface is considered wet, this is the difference between the saturated vapour pressure at the surface temperature minus the vapour pressure of the environment. The latent heat flux is equal to this vapour pressure difference multiplied by the conductance to transfer derived from wind speed and surface characteristics (Dalton, 1802), the so-called *wind function* ($\mathrm{f}(u_2)$) and multiplied by the latent heat of vaporization of water, λ (this will be discussed later):

$$\lambda E = \lambda\, \mathrm{f}(u_2)\left[e_s(T_s) - e_2\right] \tag{2.3}$$

The symbol $e_s(T_s)$ indicates the saturated vapour pressure at the temperature of the surface, e_2 is the vapour pressure measured at screen height (usually two meters above the surface). The relationship between temperature and saturated vapour pressure is not linear and can be approximated by several empirical formulas (a commonly used, simple and fast module is the module SVPS1, see Appendix IV; two others are available on request).

Similar to equation (2.3) the flux of sensible heat is:

$$H = \gamma\lambda\, \mathrm{f}(u_2)(T_s - T_2) \tag{2.4}$$

where (T_s - T_2) is the temperature difference between surface and air, and γ is the psychrometer constant.

The key question of this system of equations is to find the surface temperature at which equations (2.2), (2.3) and (2.4) are satisfied (the dependence of R_n on T_s is only slight and is ignored here). Although methods are available that iteratively determine the surface temperature, it was Penman (1948) who was able to eliminate the surface temperature by approximating the equation for exchange of latent heat (2.3) by using a linear relationship between temperature and saturated vapour pressure. In this way a straightforward solution for λE can be obtained for (2.2). The linearization stems from the notion that under practical circumstances, the surface temperature is often close to the environment temperature so that the saturated vapour pressure at the surface temperature can be approximated by:

$$e_s(T_s) \cong e_s(T_2) + s(T_s - T_2) \tag{2.5}$$

The quantity s is the slope of the saturated vapour pressure curve around T_2, the temperature at 2 m above the surface. The formula obtained by Penman is known as the combination equation (derivation not shown here):

$$E_{PM} = \frac{1}{\lambda}\frac{sR_n + \gamma\lambda\, \mathrm{f}(u_2)(e_s(T_2) - e_2)}{s + \gamma} \tag{2.6}$$

A great advantage of this formula is that weather data have to be measured only at one height above the surface contrary to earlier methods that required additional measurements of the surface temperature.

Through the elimination process, the quantity $\mathrm{f}(u_2)(e_s(T_2)\text{-}e_2)$ has appeared in the numerator of equation (2.6). This quantity is known as the isothermal evaporation (E_a) because it is the evaporation rate given the condition that the surface temperature is equal to T_2 . The value of the net radiation to satisfy this condition is when $R_n = \lambda E_a$:

$$\lambda E = \frac{s\lambda E_a + \gamma\lambda E_a}{s + \gamma} = \lambda E_a \frac{s + \gamma}{s + \gamma} = \lambda E_a \tag{2.7}$$

Equation (2.6) can also be written as the sum of two 'forces' driving the evaporation, a radiation term E_r and an aerodynamic term E_d:

$$E_{PM} = E_r + E_d = \frac{1}{\lambda}\left(\frac{sR_n}{s + \gamma} + \frac{\gamma\lambda E_a}{s + \gamma}\right) \tag{2.8}$$

In the following sections we will discuss the net radiation R_n and wind function $\mathrm{f}(u)$ in more detail.

2.1.2. Net Radiation R_n

Net radiation is defined as the net rate of absorption of radiation energy throughout all wavelengths by the water, soil or crop surface. Net radiation is an important quantity in the calculation of the Penman evaporation because the weather conditions under average growing seasons are normally such that the radiation term (E_r) is several times larger than the aerodynamic term (E_d, see also section on Makkink formula). Two different wavelengths bands are mainly involved due to the differences in surface temperature of the sun and the earth. These are short-wave radiation (150-4000 nm) as emitted by the sun, and long-wave radiation as emitted by the earth (upward) and the sky (downward, 4000-50000 nm, = thermal radiation). Due to the comparatively low surface temperature of the earth's surface, the emission of short-wave radiation by the earth is negligible. The upward flux of short-wave radiation thus consists largely of reflection. The net radiation can be written as:

$$R_n = (1-a)R_s - R_{l,up} + R_{l,down} \tag{2.9}$$

The daily average value of the reflection coefficient a (= albedo) for a water surface is usually taken as 0.06. Ten Berge (1990) compiled a list with reflection coefficients for soil surfaces which is reproduced in Table 2.1.

Table 2.1 Reflection coefficients of soils for short-wave radiation, taken from Ten Berge (1980)

Soil type	Wet	Dry	Source
Dune sand	0.24	0.37	Buttner & Sutter, 1935
Arenosa sand	0.22	0.38	Graser & Bavel, 1982
Yuma sand	0.18	0.42	Gold & Ben Asher, 1976
Williams sand	0.14	0.26	Aase & Idso,1975
Avondale sand	0.14	0.30	Idso *et al.*, 1975
Tippera clay loam	0.14	0.23	Kalma & Badham, 1972
Swifterbant silt loam	0.13	0.31	Ten Berge, 1990
Grey soil	0.11	0.27	Kondrat'ev, 1954
Red-brown clay loam	0.10	0.20	Piggin & Schwertfeger, 1973
Sandy loam	0.10	0.17	Feddes, 1971
Oudelande sandy loam	0.08	0.20	van der Heide & Koolen, 1980
Clay	0.08	0.14	Feddes, 1971
Black soil	0.08	0.14	Kondrat'ev, 1954

A reflection coefficient of 0.11 appears to be a reasonable average value for most wet non-sandy soils. The reflection coefficients of sandy soils, however, are very dependent on organic matter content, which is why the reflection coefficient of Dune sand in Table 2.1 is much higher than that of the other soils.

For crops, the reflection coefficient for short-wave radiation varies between 0.15 and 0.25 (Doorenbos & Pruitt, 1977, Buishand & Velds, 1980, see van Laar *et al*, 1992, p. 33 for a description of the calculation of crop reflection coefficients).

Often the value of R_s is not measured directly but has to be derived from sunshine duration measurements recorded with a Campbell-Stokes sunshine recorder (see Doorenbos & Pruitt, 1977). The Ångström formula has to be used for that purpose.

The long-wave radiation can be separated into outgoing and incoming long-wave radiation ($R_{l,up}$ and $R_{l,down}$). The outgoing flux can be described by the well known Stefan-Boltzmann equation which relates surface temperature to radiative emission of energy:

$$R_{l,up} = \varepsilon\sigma T_2^4 \tag{2.10}$$

Usually, black-body behaviour of the water, soil or crop surface is assumed so the ε = 1. Theoretically, the surface temperature has to be used in (2.10) requiring either a two step calculation with an unmodified Penman or a modified Penman equation with linearization of (2.10) around T_2. In standard Penman calculations, however, this is usually not done (see Section 2.1.4 on effects of linearization).

The incoming long-wave radiation is generally smaller than the outgoing flux. Also clear skies tend to emit less long-wave radiation than overcast skies so that at night, surfaces cool down more rapidly under clear skies. Because the air temperature at screen height determines the vertical temperature profile of the air to some extent, incoming long-wave radiation is correlated to T_2. The low emissivity of air, however, does not allow the use of an uncorrected Stefan-Boltzmann equation. Two practical approaches exist to calculate $R_{l,down}$; the methods by Brunt (1932) and by Swinbank (1963). Both formulas estimate $R_{l,down}$ for clear skies, corrections for overcast conditions have been proposed.

The formula developed by Brunt is valid for clear skies and essentially calculates an emissivity coefficient to be used in the Stefan-Boltzmann equation:

$$R_{l,down} = \left(B_c + B_d\sqrt{e_2}\right)\sigma T_2^4 \tag{2.11}$$

The coefficients B_c and B_d are location specific, example values are given in Table 2.2:

Table 2.2 Values to be used for coefficients B_c and B_d in the Brunt formula to calculate sky long-wave radiation. Some values were taken from Ten Berge (1990). More values can be found in Arnfield (1979).

B_c	B_d $(kPa^{-1/2})$	Source
0.44	0.250	Penman, 1956
0.53	0.212	Buishand & Velds, 1980
0.51-0.60	0.187-0.206	Unsworth & Montheith, 1975
0.60-0.75	0.054-0.180	Wartena *et al.*, 1973
0.605-0.75	0.152	Sellers, 1965
0.61	0.158	Budyko, 1958
0.62	0.111	Stroosnijder & Van Heemst, 1982

Clouds have greater long-wave emissivities than a clear sky. Normally the apparent sky temperature is around 20 °C below screen temperature; with overcast skies this reduces to around 2 °C. The effect of cloudiness is normally introduced by multiplication of the net long-wave radiation formula by a cloudiness factor:

$$R_{n,l} = \left(R_{l,up} - R_{l,down}\right)\left(p + (1-p)\frac{n}{N}\right) \tag{2.12}$$

p = 0.2 (KNMI, in Buishands & Velds, 1980)
p = 0.1 (Penman, 1956)

As has been pointed out by De Bruin (1979), (2.12) is physically not correct as the effect of cloudiness should apply to $R_{l,down}$ only. Nevertheless, (2.12) gives satisfactory results.

Another approach to find $R_{l,down}$ is followed in the formula derived by Swinbank (1963). Swinbank concluded that $R_{l,down}$ could be related very accurately to temperature only without the need to derive location-specific regression coefficients. This formula was found to give a good fit between measured and computed values of $R_{l,down}$ across different latitudes (Swinbank, 1963; Arnfield, 1979). Both the Brunt and the Swinbank method can optionally be used in the Penman subprogram. The most useful form of the Swinbank formula is:

$$R_{l,down} = 4.59 \cdot 10^{-8} T_2^6 \tag{2.13}$$

(Note that the screen temperature is raised to the power six instead of four). Holtslag & Van Ulden (1983) modified this formula to include the effect of cloudiness derived for higher latitudes by Paltridge & Platt (1976):

$$R_{l,down} = 4.59 \cdot 10^{-8} T_2^6 + 5.184 \cdot 10^6 \left(1 - \frac{n}{N}\right) \tag{2.14}$$

The numerical behavior of this formula was found to be unsatisfactory, because the net long-wave radiation calculated from (2.10) and (2.13) can switch from a net upward flux of energy to a net downward flux under cloudy conditions and high screen temperatures. This is physically possible (if the soil is colder than the cloud base), but cannot be detected with this formula. We have adopted a different approach to include cloudiness, which gives a very good correlation with the Brunt formula and does not suffer from the deficiency of (2.14)

The approach followed adjusts (2.13) by using the atmospheric transmission (α) as an estimator of cloudiness. The proposed equation is:

$$R_{l,down} = \frac{\alpha\left(4.59 \cdot 10^{-8} T_2^6 - \sigma T_2^4\right)}{0.7} + \sigma T_2^4 \tag{2.15}$$

The basis of (2.15) is the assumption that short-wave irradiation of a clear sky is around 70% of the Angot value (so that α = 0.7), if this is applied to (2.13), (2.15) should be the result. A linear relationship is assumed between α and $R_{l,down}$ between a = 0.7 and a = 0, as in the cloud correction of the Brunt formula, at α = 0 it is assumed that the sky's temperature is T_2.This is illustrated in Figure 2.1.

The Brunt and Swinbank methods are compared for Dutch weather conditions (Wageningen, 1980 and 1981) in Figure 2.2. The coefficients used in the Brunt formula are those that are used by KNMI (Buishand & Velds, 1980), B_c = 0.53, B_d = 0.212, p = 0.2, relative sunshine duration was determined from measured global radiation using the Ångström formula with a and b values used by KNMI (A_a = 0.2, A_b = 0.48, see Buishand & Velds, 1980). Negative values of net radiation occur on some winter days when incoming short-wave radiation is less than net outgoing long-wave radiation, and is not caused by the above mentioned deficiency of (2.14). An almost 1:1 linear relationship is found which proves the agreement between the Brunt and Swinbank approaches. The Swinbank approach, however, was considered to be superior to the Brunt formula, because: 1) only temperature is needed, 2) correction for latitude is not necessary, and 3) A_a and A_b do not have to be estimated.

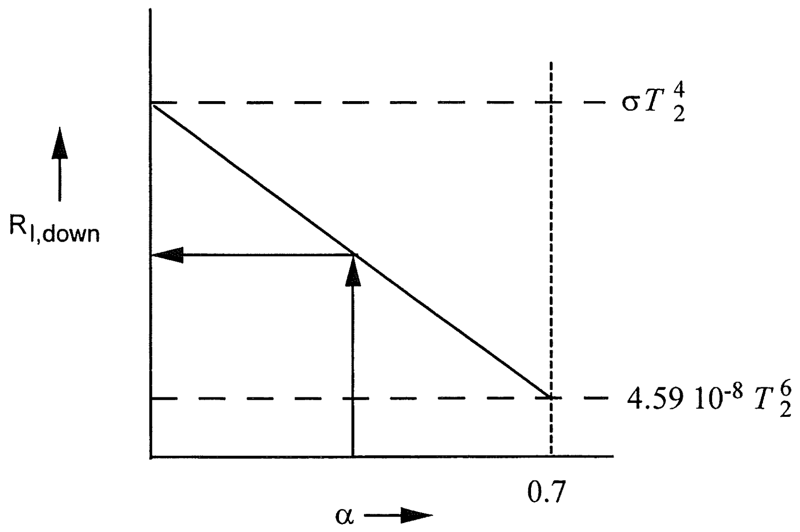

Figure 2.1 Method by which long-wave radiation from the sky is corrected for cloudiness, α = atmospheric transmission, $R_{l,down}$ is thermal radiation from the sky.

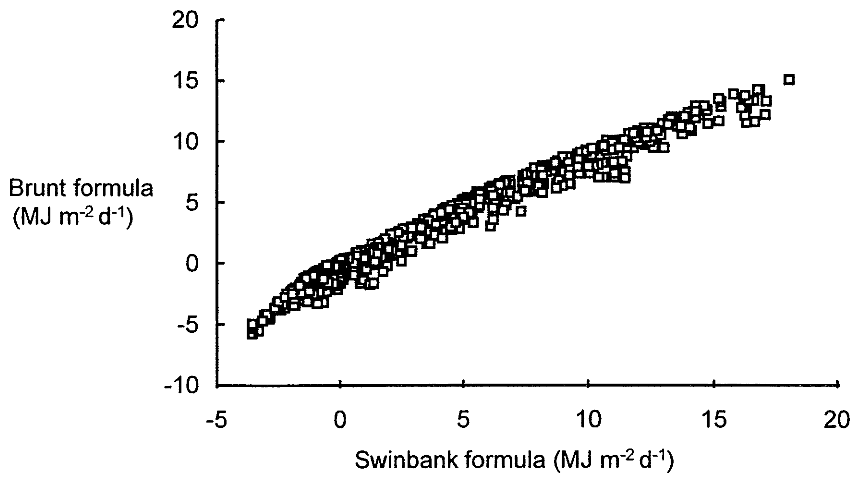

Figure 2.2 Relation between net radiation obtained with the adapted Swinbank formula (2.15) and with the Brunt formula (2.12) using daily weather data from Wageningen, The Netherlands, 1980 and 1981. Surface albedo was set at 10%, Brunt B_c and B_d values of 0.53 and 0.212 were used, respectively.

2.1.3. Wind function $\mathrm{f}(u)$

The wind function is the name of a formula that estimates conductance to transfer of latent (2.3) and sensible heat (2.4) from the surface to the reference height. In the Penman method most often empirical wind functions are used that are implicitly parameterized for effects of roughness of the surface and atmospheric stability. Wind functions that are physically more sound are also available but will not be treated in detail here.

The wind function that is mostly used for open water and soil surfaces is (Penman, 1956):

$$\mathrm{f}(u_2) = 2.63(0.5 + 0.54u_2) \qquad (2.16)$$

This formula has been modified to conform to the units of this report which explains the difference with the expressions for open water found normally in the literature (e.g. Withers & Vipond, 1974). The units of (2.16) are: $\mathrm{f}(u_2)$ in mm (water) d^{-1} kPa^{-1} and u_2 in m s^{-1} (2.63 is a unit conversion factor). The wind function that is mostly used for short grass crops with a closed canopy is:

$$\mathrm{f}(u_2) = 2.63(1 + 0.54u_2) \qquad (2.17)$$

Note: Doorenbos & Pruitt (1977) derived a wind function from experimental data that differs somewhat from (2.17). This is caused to a considerable extent by the way components of the Penman formula are calculated (Doorenbos & Pruitt,1977).

The larger value of the wind function for crops (the intercept is larger, 1 for crops vs. 0.5 for open water) is due to the greater surface roughness of crop canopies compared to open water. Tall, fully closed crops even show greater aerodynamic roughnesses and, consequently, greater conductances to transfer of vapour and heat. At equal net radiation values, tall crops therefore tend to transpire more than short crops. Another important point to note is that the linear shape of these wind functions is actually a fit of a linear function on a limited set of measurements which follow a curvilinear path (e.g. Penman, 1948). Under truly isothermal conditions, the function should go through the origin because still air cannot transfer heat and vapour. Often, however, it is doubtful if isothermal conditions existed and the intercept is partly caused by buoyancy effects at low wind speeds. This is the reason that the wind functions (2.16) and (2.17) are not very accurate at wind speeds close to zero under isothermal conditions.

Errors in the wind function, however, do not influence evaporation very much because under normal conditions in a growing season, the radiation term is much greater than the aerodynamic term, which means that errors in the estimation of the wind function will have less effect than inaccuracies in the net radiation. This is not necessarily true for tall crops, however.

For crops taller than grass several formulas have been proposed including that of Thom & Oliver (1977):

$$\mathrm{f}(u_2) = \frac{136(1 + 0.54u_2)}{\ln^2 \dfrac{2-d}{z_0}} \qquad (2.18)$$

where d and z_0 are displacement height and roughness length of the logarithmic wind profile (estimated with $d = 0.7\ l$ and $z_0 = 0.1\ l$, l being the height of the crop in meters). It can be shown that this formula gives roughly the same relationship as (2.17) when the height of the crop is set at 0.02 m.

2.1.4. Effects of linearization of the Penman equation

The linearization of the relation between the saturated vapour pressure and temperature that was the basis for the derivation of the Penman formula introduces errors in the calculation of λE when the equilibrium surface temperature differs from T_2 . Only when the surface temperature equals T_2, the Penman equation yields an exact solution, given the uncertainties in input data; this situation occurs when $R_n = \lambda E_a$. Part of the error can be avoided by a second linearization around T_2 namely of outgoing long-wave radiation instead of a zero-order approach. In (2.10) the outgoing long-wave radiation was approximated by taking the air temperature as representative for the surface temperature. In Figure 2.3 a comparison is made between the standard Penman equation (2.6), with zero-order outgoing long-wave radiation, and an iterative Penman procedure that searches for the equilibrium temperature.

The temperature of the surface can be calculated from the sensible heat flux and the resistance to transfer of heat from the surface to reference height. This resistance can in turn be derived from the wind function. Therefore, the empirical form of the wind function has to be converted to an equation describing a resistance (with unit s m^{-1}). By applying Fick's law of diffusion over a finite distance, the general form of the evaporation equation can be written as:

$$E\left(\mathrm{kg\ m^{-2}\ s^{-1}}\right) = \frac{concentration\ difference\left(\mathrm{kg\ m^{-3}}\right)}{r\left(\mathrm{s\ m^{-1}}\right)} \tag{2.19}$$

If we equate (2.3) and (2.19) and write VPD for the difference in vapour pressure between surface and reference height:

$$\frac{\mathrm{f}(u_2)VPD}{86400} = \frac{p \cdot VPD}{r} \tag{2.20}$$

where g is a conversion factor derived from the gas law of Boyle-Gay Lussac to convert VPD (which is a difference of pressure) to a concentration difference:

$$g\left(\mathrm{kg\ m^{-3}\ kPa^{-1}}\right) = \frac{1000 \cdot 0.018016}{R(T_2 + 273.16)} \tag{2.21}$$

The factors 1000 and 0.018016 are the correction for VPD in kPa and the weight of one mole of water in kg's, respectively. The symbol R is the universal gas constant (= 8.31436 J °C^{-1} mole^{-1}). The resistance r (in s m^{-1}) now becomes:

$$r = \frac{86400 \cdot 1000 \cdot 0.018016}{\mathrm{f}(u_2) \cdot R \cdot (T_2 + 273.16)} \tag{2.22}$$

The loss of latent and sensible heat as given in (2.3) and (2.4) can now be reformulated in:

Latent heat: $\lambda E = \dfrac{g \cdot VPD}{r}$ often written as $\lambda E = \dfrac{VPD \cdot \rho c_p}{r\gamma}$ (2.23)

Sensible heat: $H = \dfrac{T_s - T_2}{r} \rho c_p$ (2.24)

The temperature difference between surface and screen height can be calculated from (2.24) by eliminating H from the radiation balance (2.2) and T_s - T_2 from (2.24):

$$T_s - T_2 = r\frac{R_n - \lambda E}{86400 \rho c_p} \quad (2.25)$$

The correct slope to be used in the iterated Penman equation is now:

$$s = \frac{e(T_s) - e(T_2)}{T_s - T_2} \quad (2.26)$$

In Figure 2.3 a comparison is made between the standard Penman equation and the value derived from the iterative approach. Although variations occur as large as 1 mm, the average differences are around 0.2 mm.d^{-1}. Given an average daily water loss to the atmosphere in The Netherlands between 3 and 5 mm, the relative differences are around 5% during the growing season. The approach above can be used successfully for situations where it is suspected that large differences between surface temperature and temperature at screen height occur. In general, under conditions where R_n is much smaller or much larger than λE_a the surface is either lower or higher in temperature.

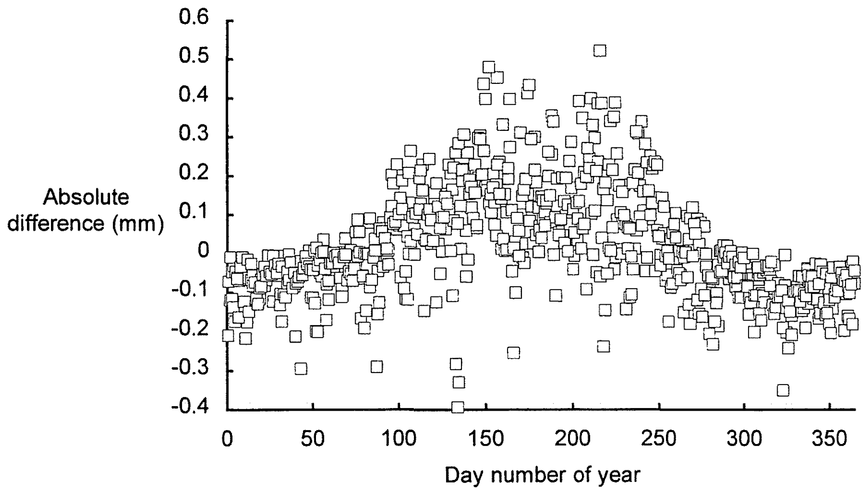

Figure 2.3 Differences of open water evaporation between 'single Penman' and 'iterative Penman' procedure. Weather data from Wageningen, The Netherlands, 1980 and 1981 were used.

2.2. Priestley-Taylor method

2.2.1. Theory

The Priestley-Taylor method (Priestley-Taylor, 1972; De Bruin, 1983) is a simplified Penman method, requiring only radiation and temperature as inputs. This is justified by the observation that evapotranspiration is generally more determined by levels of net radiation than by air dryness and wind. So, in the Penman equation, E_r is larger than E_d. The ratio between E_r and E_d is plotted in Figure 2.4. This graph shows that during the months April to September, this ratio is about two; however, in the remaining months this ratio, however, is less than two. Therefore, application of the Priestley-Taylor formula for Dutch winter months is not possible (this also applies to the Makkink formula). This is not necessarily true for other climates, as will be shown in Section 2.2.2.

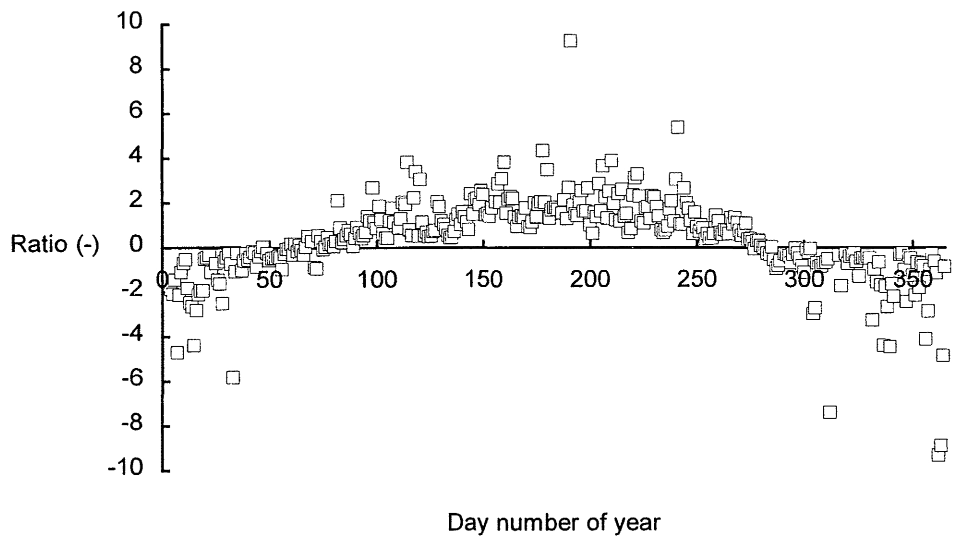

Figure 2.4 Ratio of radiation-caused component over air dryness and wind-caused component of evapotranspiration for Wageningen, The Netherlands, 1980 (Calculated with Penman subroutine).

The Priestley-Taylor evapotranspiration consists only of the radiation-driven part of the Penman equation multiplied by a coefficient (C_{PT}):

$$E_{PT} = C_{PT} \frac{1}{\lambda} \frac{R_n s}{s+\gamma} \tag{2.27}$$

Comparison of (2.27) with the Penman equation applied to a short well-watered crop (crop albedo: $a = 0.25$, wind function: $f(u_2) = 2.63\ (1+0.54u_2)$), however, does not give a 1:1 relationship. When Penman is parameterized for open water, the relationship between E_r and E_d is about 4:1, resulting in a C_{PT} value of 1.26. When Penman is parameterized for a short well-watered crop, this ratio is about 2:1 (see Figure 2.4), resulting in a C_{PT} value of 1.42 (determined for Wageningen, 1981 weather data between day 91 and 273). The formula that we use in the Priestley-Taylor subprogram is now:

$$E_{PT} = 1.42 \frac{1}{\lambda} \frac{R_n s}{s + \gamma} \tag{2.28}$$

As has been described in the previous chapter, two methods exist to calculate net long-wave radiation, the Brunt and the Swinbank formula. However, the Brunt formula requires vapour pressure data, cloudiness and average daily air temperature, whereas the Swinbank formula requires only average daily air temperature and cloudiness. We prefer to use the latter method as the Priestley-Taylor method will normally be used in cases where only a limited amount of weather data are available.

The Priestley-Taylor formula appears to be purely based on empiricism. De Bruin (1987) however, states that recent research has shown that there is a more fundamental basis for the formula. We will not discuss this here any further.

2.2.2. Comparison of Penman vs. Priestley-Taylor for different locations

Figure 2.5 compares, the methods of Penman and Priestley-Taylor for Wageningen, The Netherlands, 1980. The Priestley-Taylor calculations have been based on equation (2.28) with the Swinbank formula used for net long-wave radiation. Application of Priestley-Taylor during Dutch winter months is not possible. Often net radiation is negative in the winter months and, as the Priestley-Taylor formula basically only uses net radiation, Priestley-Taylor predicts dew formation whereas the actual evapotranspiration should be positive. This can be seen in the graph from the positive differences in the winter months.

The situation is very much different for a humid climate such as in the Philippines. Figure 2.6 shows the corresponding graph for Los Baños, The Philippines, 1981. This graph shows that application of the Priestley-Taylor formula is possible in this type of climate.

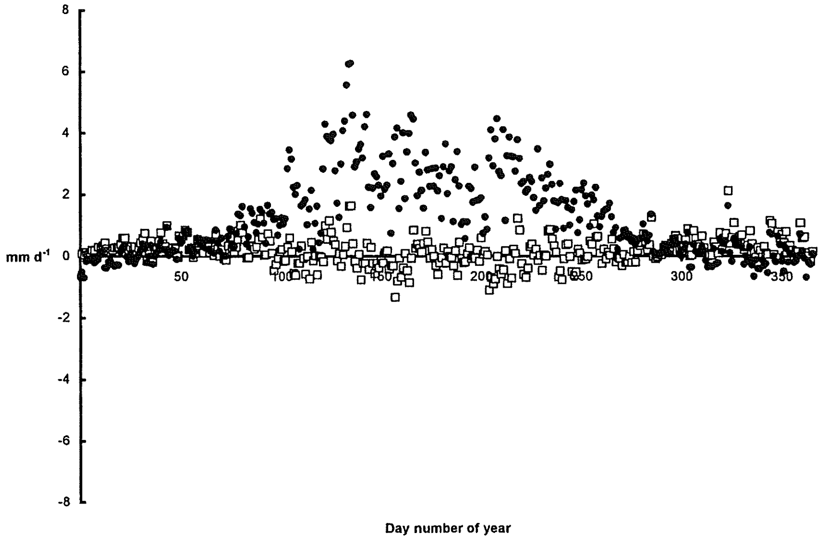

Figure 2.5 Penman evapotranspiration (dots) and difference between Penman (calculated for short crop, well watered) and Priestley-Taylor evapotranspiration (squares) for Wageningen, The Netherlands, 1980.

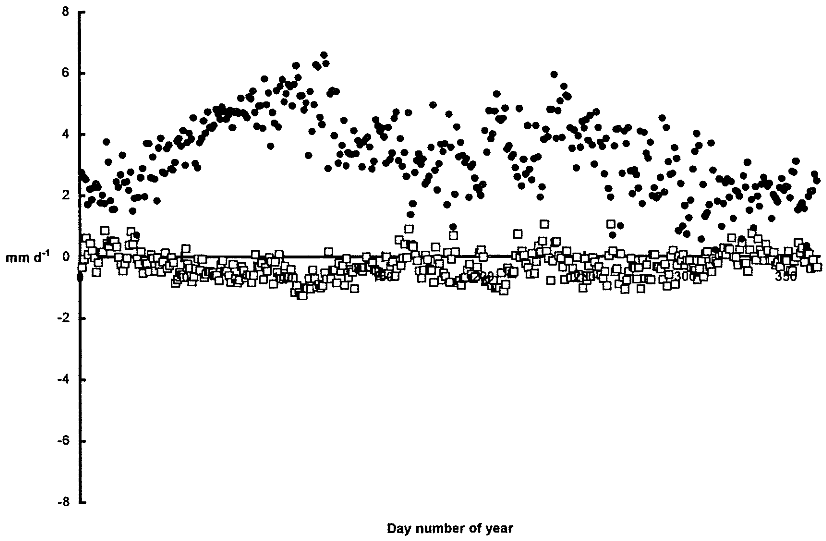

Figure 2.6 Penman evapotranspiration (dots) and difference between Penman (calculated for short crop, well watered) and Priestley-Taylor evapotranspiration (squares) for Los Baños, The Philippines, 1981.

A more semi-arid climate such as in Israel gives a result similar to the humid climate of the Philippines. Figure 2.7 compares the methods of Penman and Priestley-Taylor for Migda, Israel, 1978.

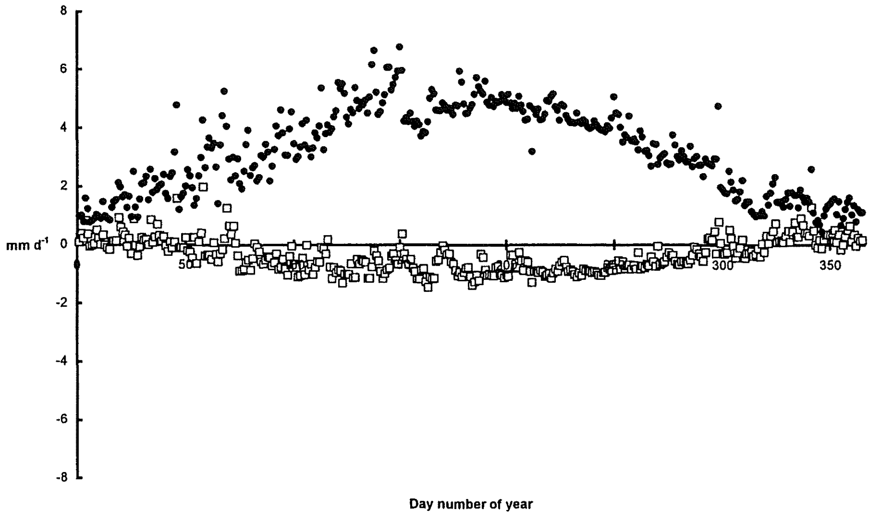

Figure 2.7 Penman evapotranspiration (dots) and difference between Penman (calculated for short crop, well watered) and Priestley-Taylor evapotranspiration (squares) for Migda, Israel, 1978.

2.3. Makkink method

2.3.1. Theory

The Makkink method (Makkink, 1957) can be considered as a simplified Priestley-Taylor formula, requiring, similar to Priestley-Taylor, only radiation and temperature as inputs. The difference is that instead of using net radiation and temperature, the Makkink formula uses incoming short-wave radiation (R_s) and temperature. This can be done because, on average, a constant ratio exists between net radiation (R_n) and short-wave radiation (R_s, ratio ≅ 50%). The Makkink formula can thus be derived from the Priestley-Taylor formula:

$$E_{MK} = C_{MK} \frac{1}{\lambda} \frac{R_s s}{s+\gamma} \tag{2.29}$$

.

Similar to the derivation of the calibration factor for the Priestley-Taylor method, we have determined a calibration factor (C_{MK} = 0.63). The formula applied in the Makkink subprogram now is:

$$E_{MK} = 0.63 \frac{1}{\lambda} \frac{R_s s}{s+\gamma} \tag{2.30}$$

An advantage of the Makkink formula compared to the Priestley-Taylor formula is that no calculations for long-wave radiation are required. Application of the Makkink formula in Dutch winter months is not possible. This is not necessarily so for other climates, as will be shown in the next Section.

2.3.2. Comparison of Penman vs. Makkink for different locations

Figure 2.8 compares the methods of Penman and Makkink for Wageningen, The Netherlands, 1980. The Makkink calculations are based on (2.30). Similar to the Priestley-Taylor method, application of Makkink in the Dutch winter months is not possible. Obviously, the Makkink formula does not suffer from the deficiency that Priestley-Taylor evapotranspiration has, namely negative values while in fact evapotranspiration is positive. This can be seen in the graph from the large negative differences compared to the absolute values of the Penman method.

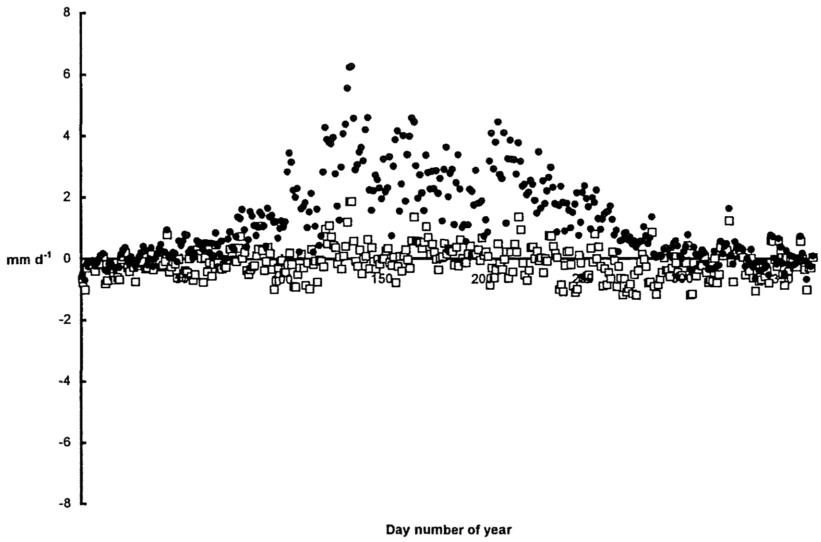

Figure 2.8 Penman evapotranspiration (dots) and difference between Penman (calculated for short crop, well watered) and Makkink evapotranspiration (squares) for Wageningen, The Netherlands, 1980.

Similar to Priestley-Taylor, the situation is very different for a humid climate such as in the Philippines. Figure 2.9 shows the corresponding graph for Los Baños, The Philippines, 1981; it appears that application of the Makkink formula is possible in this type of climate.

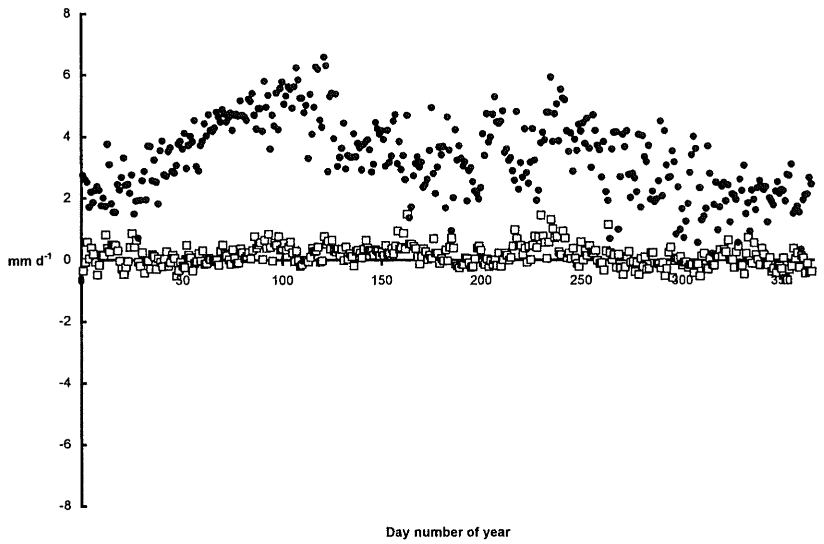

Figure 2.9 Penman evapotranspiration (dots) and difference between Penman (calculated for short crop, well watered) and Makkink evapotranspiration (squares) for Los Baños, The Philippines, 1981.

A more semi-arid climate such as in Israel gives results similar to the situation of the humid climate of The Philippines. The results for Migda, Israel, 1978 are shown in Figure 2.10. When the Makkink formula is applied in a model for a semi-arid climate, correction factors for each time of the year are required here to compensate for the underestimation of evapotranspiration during autumn, winter and spring. However, Priestley-Taylor is the preferred method in this type of climate since it has the same data requirements as the Makkink method.

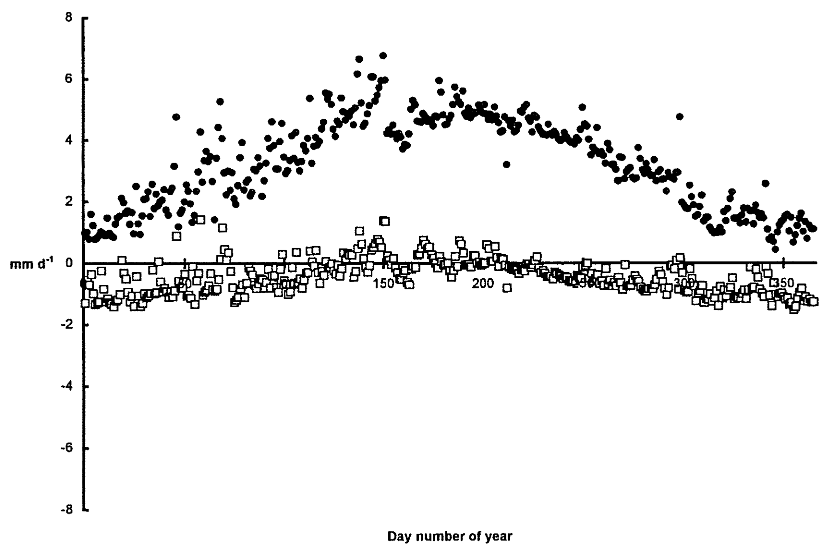

Figure 2.10 Penman evapotranspiration (dots) and difference between Penman (calculated for short crop, well watered) and Makkink evapotranspiration (squares) for Migda, Israel, 1978.

3. User guide

3.1. Availability of the described modules

The modules as they are described in this manual are written in standard Fortran-77 with the exception of the IMPLICIT NONE statement. This statement, however, is supported by almost all Fortran-77 compilers. The modules are available on 1.44 Mb MS-DOS compatible floppy disk. To use the modules in unaltered form, you also need a recent version of the TTUTIL utility library. If you are interested in working with these modules and TTUTIL, send a request to:

AB-DLO
Software Product Support
c/o P.W.J. Uithol
P.O. Box 14
6700 AA Wageningen
The Netherlands

or through e-mail to: SPS@AB.DLO.NL

3.2. Module SETPMD (Penman evapotranspiration)

3.2.1. Purpose

This module calculates reference evapotranspiration in a manner similar to Penman (1948). To obtain crop evapotranspiration, multiplication with a Penman crop factor should be performed. Calculations can be carried out for three types of surfaces: water, wet soil, and short grass (ISURF = 1,2,3 resp.). For the calculation of the long-wave radiation, a choice can be made between the methods of Brunt (1932) and Swinbank (1963) (through the values of the input variables ANGA and ANGB). When the input variable TMDI is set at zero, a single calculation is done and an estimate is provided of the temperature difference between the environment and the surface (DT). If the absolute value of DT is large, an iterative Penman calculation can be carried out which continues until the new surface temperature differs by no more than TMDI from the surface temperature calculated with the single step procedure. The Brunt formula is parameterized with KNMI (Dutch Royal Meteorological Institute) data. To obtain actual crop transpiration from reference evapotranspiration on the basis of leaf area index, the method of Van Laar *et al.* (1992) can be followed. To obtain actual crop transpiration from reference evapotranspiration on the basis of date in the growing season, the method of Feddes (1987) can be followed.

3.2.2. Usage

```
CALL  SETPMD (IDOY, LAT , ISURF, RF, ANGA, ANGB, TMDI, RDD, TMDA, WN, VP,
               ETD , ETRD, ETAE , DT)
```

3.2.3. Input / Output

Table 3.1 lists the input and output arguments of the module SETPMD. Each argument should get the appropriate declaration in the calling program. Input arguments should be initialized. Two types of classes of arguments are distinguished in Table 3.1: input arguments to the module SETPMD marked with **I** and output arguments marked with **O**.

Table 3.1 Name, type, description, units and class of formal parameters of the module SETPMD

Variable	Type	Description	Units	Class
IDOY	I4	Day number (Jan 1st = 1)	d	I
LAT	R4	Latitude of the site	decimal degrees	I
ISURF	I4	Type of surface (1 = open water, 2 = soil surface, 3 = short grass)	-	I
RF	R4	Reflection (= albedo) of surface (use 0.06 for water, 0.11 for soils and 0.25 for short grass, see van Laar *et al.*, 1992))	-	I
ANGA	R4	A value of Ångström formula (if zero and ANGB is zero, the Swinbank method for long-wave radiation is used, otherwise the Brunt method is used)	-	I
ANGB	R4	B value of Ångström formula (if zero and ANGA is zero, the Swinbank method for long-wave radiation is used, otherwise the Brunt method is used)	-	I
TMDI	R4	Temperature tolerance (if > 0, iterative Penman is started)	°C	I
RDD	R4	Daily short-wave radiation	J m^{-2} d^{-1}	I
TMDA	R4	24 hour average temperature	°C	I
WN	R4	24 hour average windspeed	m s^{-1}	I
VP	R4	24 hour average vapour pressure	kPa	I
ETD	R4	Penman evapotranspiration	mm d^{-1}	O
ETRD	R4	Radiation-driven part of `ETD`	mm d^{-1}	O
ETAE	R4	Dryness-driven part of `ETD`	mm d^{-1}	O
DT	R4	Estimated temperature difference between surface height and reference height	°C	O

3.2.4. Optional switches

Three input parameters of the module SETPMD are used for internal options that can be defined by the user. These options are: type of surface used, method used for calculation of long-wave radiation and the accepted temperature tolerance, which switches between the single and the iterative Penman procedure. The variables `ISURF`, `ILW` and `TMDI` should therefore get appropriate values in the main program.

Type of surface (ISURF)
Calculation of reference evapotranspiration according to Penman can be carried out for three types of surfaces. When

ISURF = 1: calculation for open water surface (use RF = 0.06),
ISURF = 2: calculation for a wet soil (use RF = 0.11),
ISURF = 3: calculation for short grass (use RF = 0.25).

Please note that by giving a value to the variable ISURF, the corresponding reflection coefficient RF is not automatically assigned; one has to assign the corresponding albedo in the calling program. The value of RF can be calculated from crop and top soil characteristics, see Van Laar *et al.* (1992).

Calculation of long-wave radiation (ANGA and ANGB)
With the variables ANGA and ANGB one can choose whether the calculation of long-wave radiation is done according to the Swinbank formula or to the Brunt formula.

ANGA = 0, ANGB = 0 : Swinbank formula
otherwise : Brunt formula

Only the Brunt formula requires ANGA and ANGB so that the user has to take care to supply valid values to the routine. It is not enough simply to choose non-zero numbers if one wants to use the Brunt formula.

Temperature tolerance (TMDI)
By giving a value to the real variable TMDI, the module SETPMD switches between the single (TMDI = 0) and the iterative Penman procedure (TMDI equals the accepted temperature tolerance). Note that the estimated temperature difference between reference height and surface height is returned through the variable DT even if iteration is switched off. If DT is very large one could decide to use an iterative Penman procedure.

3.2.5. Example program

This example program shows the use of the module SETPMD: it calculates the evapotranspiration of a short, well watered grass crop in July with the single Penman procedure using the Brunt formula for long-wave radiation. The correct value of ETD in this example is 4.57.

```
PROGRAM TEST
IMPLICIT NONE
REAL LAT, RF, ANGA, ANGB, TMDI, RDD, TMDA, WN, VP
REAL ETD, ETRD, ETAE, DT
INTEGER IDOY, ISURF

IDOY  = 195
LAT   = 52.
ISURF = 3
RF    = 0.25
ANGA  = 0.2
ANGB  = 0.48
TMDI  = 0.
RDD   = 20.E6
TMDA  = 20.
WN    = 2.5
VP    = 1.
```

```
 CALL SETPMD (IDOY, LAT , ISURF, RF, ANGA, ANGB, TMDI,
&             RDD , TMDA, WN   , VP,
&             ETD , ETRD, ETAE , DT)

 WRITE (*,*) ETD

 END
```

3.2.6. Other modules needed

This section describes shortly the function of the external modules that are called by SETPMD.

Module SASTRO: The module SASTRO is called to calculate the daily extraterrestrial radiation in J m^{-2} d^{-1} from day number and latitude. Daily extraterrestrial radiation is used to calculate daily atmospheric transmission.

Module SVPS1: The module SVPS1 is called to calculate the saturated vapour pressure in kPa at a certain temperature and the slope of the saturated vapour pressure curve against temperature in kPa °C^{-1}.

3.2.7. Control of errors and warnings

During execution of the module SETPMD, several checks are carried out. These checks can lead to warnings and error messages. When a warning message appears on the screen, the simulation run will continue. Error messages, however, are fatal and stop the execution. When an error message appears on the screen, the screen is held until the <RETURN> key is pressed. Execution of the program will be terminated then and the user will return to the command line (prompt) of the computer. Note that in principle, only messages from SETPMD are discussed here, because SETPMD also uses other modules, it is possible that other modules also report messages to the user.

This section explains under which conditions warning and error messages can occur and how the cause can be removed. The error and warning messages are listed in order of appearance in the module.

`ERROR in SETPMD: Undefined iteration`

The value of the temperature tolerance input parameter (TMDI) is negative. Within the module SETPMD, potential evapotranspiration according to the Penman method can be calculated with a single and with an iterative procedure. If TMDI is set at zero, SETPMD will use the single procedure, if TMDI is greater than zero SETPMD will use the iterative procedure. Change the current value of TMDI to zero or more.

`WARNING from SETPMD: Low short-wave radiation = *.** J/m2/d`

The value of the input parameter RDD, daily short-wave radiation, has a value below 0.5 MJ m^{-2} d^{-1}. This value is low, but not impossible; if many of these warnings occur, one should check the correctness of the radiation data and/or its units.

```
WARNING from SETPMD: Low wind speed = *.** m/s
```

The value of the input parameter WN, 24 hour average wind speed, has a value below 0.2 m s^{-1}. This value is low, but not impossible; if many of these warnings occur, one should check the correctness of the wind speed data and/or its units.

```
WARNING from SETPMD: Vapour pressure more than 40% greater than saturated!
```

The value of the input parameter VP, 24 hour average vapour pressure, exceeds the saturated vapour pressure calculated at the 24 hour average temperature by more than 40%. Either the value of VP is far too high, or the value of TMDA is too low. This is in fact an impossible situation although it is treated as a warning. One should check the correctness of both vapour pressure and average temperature data and/or its units.

```
Error from SETPMD: illegal long-wave radiation option
```

The value of the input parameter ILW, which activates one of the two options to calculate long-wave radiation, differs from one (Swinbank) or two (Brunt). Change the current value of ILW to one or two.

```
Error from SETPMD: unimplemented surface value
```

The value of the input parameter ISURF is wrong. Potential evapotranspiration can be calculated for three types of surfaces: water, wet soil and short grass (ISURF values 1, 2 and 3, respectively). Change the current value of ISURF to one of these values.

```
Error from SETPMD: Cannot find equilibrium conditions
```

It was not possible for the module SETPMD to find an equilibrium condition between evaporation and surface temperature within 100 iterations of the iterative Penman procedure. Equilibrium conditions were found when the absolute difference between the variables DT, the estimated temperature difference and DTN, the estimated temperature difference at the average daily temperature, TMDA plus DT, is less than the accepted temperature tolerance in the parameter TMDI. For some reason this could not be realised.

3.3. Module SETPTD (Priestley-Taylor evapotranspiration)

3.3.1. Purpose

This module calculates reference evapotranspiration for a short well-watered grass crop in a manner similar to Priestley-Taylor (1972). To obtain actual crop evapotranspiration, multiplication with a crop factor should be done (see Van Laar *et al.*, 1992). The use of this method is basically limited to areas with large amounts of radiation.

3.3.2. Usage

```
CALL SETPTD (IDOY, LAT, RF, RDD, TMDA, ETD)
```

3.3.3. Input / Output

Table 3.2 Name, type, description, units and class of formal parameters of the module SETPTD.

Variable	Type	Description	Units	Class
IDOY	I4	Day number (Jan 1st = 1)	d	I
LAT	R4	Latitude of the site	degrees	I
RF	I4	Reflection (= albedo) of surface (see Van Laar *et al.*, 1992)	-	I
RDD	R4	Daily short-wave radiation	J m^{-2} d	I
TMDA	R4	24-hour average temperature	°C	I
ETD	R4	Priestley-Taylor evapotranspiration	mm d^{-1}	O

3.3.4. Optional switches

None

3.3.5. Example program

This example program shows the use of the module SETPTD; it calculates the evapotranspiration of short, well-watered grass crop in July according to the method of Priestley-Taylor. The correct value of ETD in this example is 3.95.

```
PROGRAM TEST
IMPLICIT NONE
INTEGER IDOY
REAL LAT, RF, RDD, TMDA, ETD

IDOY  = 195
LAT   = 52.
RF    = 0.25
RDD   = 20.E6
TMDA  = 20.

CALL SETPTD (IDOY, LAT, RF, RDD, TMDA, ETD)

WRITE (*,*) ETD

END
```

3.3.6. Other modules needed

Module SASTRO: The module SASTRO is called to calculate the daily extraterrestrial radiation in J m^{-2} d^{-1} from day number and latitude. Daily extraterrestrial radiation is used to calculate daily atmospheric transmission.

Module SVPS1: The module SVPS1 is called to calculate the saturated vapour pressure in kPa at a certain temperature and the slope of the saturated vapour pressure curve against that temperature in kPa $°C^{-1}$.

3.3.7. Control of errors and warnings

```
WARNING from SETPTD: Low short-wave radiation = *.** J/m2/d
```

The value of the input parameter RDD, daily short-wave radiation, has a value below 0.5 MJ m^{-2} d^{-1}. This value is low, but not impossible: if many of these warnings occur, one should check the correctness of the radiation data and/or its units.

3.4. Module SETMKD (Makkink evapotranspiration)

3.4.1. Purpose

This module calculates reference evapotranspiration according to Makkink (1957) for a well-watered short grass crop. To obtain crop evapotranspiration, multiplication with a crop factor should be done (see Van Laar *et al.*, 1992). The use of this method is basically limited to areas with large amounts of radiation.

3.4.2. Usage

```
CALL SETMKD (RDD, TMDA, ETD)
```

3.4.3. Input / Output

Table 3.3 Name, type, description, units and class of formal parameters of the module SETMKD.

Variable	Type	Description	Units	Class
TMDA	R4	24-hour average temperature	°C	I
RDD	R4	Daily short-wave radiation	kJ m^{-2} d^{-1}	I
TMDA	R4	Daily average temperature	°C	I
ETD	R4	Makkink's reference evapotranspiration	mm d^{-1}	O

3.4.4. Optional switches

None

3.4.5. Example program

This example program shows the use of the module SETMKD; it calculates the evapotranspiration of short, well watered grass crop according to the method of Makkink (1957). The correct value of ETD in this example is 3.51

```
PROGRAM TEST
IMPLICIT NONE
REAL RDD, TMDA, ETD

RDD  = 20.E6
TMDA = 20.

CALL SETMKD (RDD, TMDA, ETD)

WRITE (*,*) ETD

END
```

3.4.6. Other modules needed

Module SVPS1: The module SVPS1 is called to calculate the saturated vapour pressure in kPa at a certain temperature and the slope of the saturated vapour pressure curve against that temperature in kPa $°C^{-1}$.

3.4.7. Control of errors and warnings

WARNING from SETMKD: Low short-wave radiation = *. J/m2/d**

The value of the input parameter RDD, daily short-wave radiation, has a value below 0.5 MJ m^{-2} d^{-1}. This value is low, but not impossible; if many of these warnings occur, one should check the correctness of the radiation data and/or its units.

References

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Arnfield, A.J., 1979.
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Appendix I: Module SETPMD (Penman)

```
*----------------------------------------------------------------------*
* SUBROUTINE SETPMD (Subroutine Evap. Trans. PenMan Daily)             *
* Authors: Daniel van Kraalingen                                       *
* Date   : 7-March-1997                                                *
* Version: 1.1                                                         *
* Purpose: This subroutine calculates reference evapotranspiration     *
*          in a manner similar to Penman (1948). To obtain crop evapo- *
*          transpiration, multiplication with a Penman crop factor     *
*          should be done. Calculations can be carried out for three   *
*          types of surfaces: water, wet soil, and short grass         *
*          (ISURF=1,2,3 resp.). When the input variable TMDI is set to *
*          zero, a single calculation is done and an estimate is       *
*          provided of temperature difference between the environment  *
*          and the surface (DT). If the absolute value of DT is large  *
*          an iterative Penman can be carried out which continues until*
*          the new surface temperature differs by no more than TMDI    *
*          from the old surface temperature. Two types of long-wave    *
*          radiation calculations are available Swinbank and Brunt.    *
*          The switch between the two is made by choosing the right    *
*          values for ANGA and ANGB. If ANGA and ANGB are zero,         *
*          Swinbank is used, if both are positive, Brunt is used and   *
*          the ANGA and ANGB values are in the calculation of the      *
*          cloud cover.                                                *
* Refs.  : Kraalingen, D.W.G. van, W. Stol, 1997. Evapotranspiration   *
*          modules for crop growth simulation. Quantitative Approaches *
*          in Systems Analysis No. 11. DLO Research Institute for      *
*          Agrobiology and Soil Fertility (AB-DLO), The C.T. de Wit    *
*          graduate school for Production Ecology (PE). Wageningen.    *
*          The Netherlands.                                            *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (units)                                    class *
* ----   ---- ---------------                                    ----- *
* IDOY    I4  Day number within year of simulation (d)              I  *
* LAT     R4  Latitude of site (dec.degr.)                          I  *
* ISURF   I4  Switch value to choose between different surface        *
*             types (-)                                             I  *
* RF      R4  Reflection (=albedo) of surface (-)                   I  *
* ANGA    R4  A value of Angstrom formula (-)                       I  *
* ANGB    R4  B value of Angstrom formula (-)                       I  *
* TMDI    R4  Temperature tolerance (switches between single and       *
*             iterative Penman) (-)                                 I  *
* RDD     R4  Daily short-wave radiation (J.m-2.d)                  I  *
* TMDA    R4  24 hour average temperature (degrees C)               I  *
* WN      R4  Average wind speed (m.s-1)                            I  *
* VP      R4  Early morning vapour pressure (kPa)                   I  *
```

```
* ETD      R4  Potential evapotranspiration (mm.d-1)                  O  *
* ETRD     R4  Radiation driven part of potential                        *
*              evapotranspiration (mm.d-1)                            O  *
* ETAE     R4  Dryness driven part of potential evapotranspiration      *
*              (mm.d-1)                                               O  *
* DT       R4  Estimated temperature difference between surface         *
*              height and reference height (degrees C)                O  *
*                                                                        *
* Fatal error checks : TMDI < 0                                          *
*                      ISURF < 1 and > 3                                 *
*                      combination of ANGA and ANGB value, see IF line *
* Warnings           : RDD < 0.5E6                                       *
*                      WN < 0.2                                          *
*                      VP > 1.4*saturated                                *
* Subprograms called : SASTRO, SVPS1                                     *
* Required libraries : TTUTIL                                            *
* File usage         : none                                              *
*------------------------------------------------------------------------*
      SUBROUTINE SETPMD (IDOY, LAT , ISURF, RF, ANGA, ANGB, TMDI,
     &                   RDD , TMDA, WN   , VP,
     &                   ETD , ETRD, ETAE , DT)
      IMPLICIT NONE

*     Formal parameters
      INTEGER IDOY, ISURF
      REAL LAT,RF,ANGA,ANGB,TMDI,RDD,TMDA,WN,VP,ETD,ETRD,ETAE,DT

*     Local parameters
      INTEGER INLOOP,ILW
      REAL LHVAP,PSCH,SIGMA,RHOCP,RBGL,VPS,VPSL,HUM,VPD,ANGOT
      REAL DATMTR,LIMIT,RDLOI,RDLII,RDLO,RDLI,RDN,CLEAR,FU2
      REAL EA,RE,DTN,VPS2
      REAL DUMR1,DUMR2,DUMR3,DUMR4,DUMR5,DUMR6,DUMR7
      LOGICAL EQUIL

*     Parameters
      PARAMETER (LHVAP = 2454.E3, PSCH = 0.067, SIGMA = 5.668E-8)
      PARAMETER (RHOCP = 1240.  , RBGL = 8.31436)
      SAVE

*     Checks

      IF (TMDI.LT.0.) CALL FATALERR
     &   ('SETPMD','Undefined iteration')
      IF (RDD.LT.0.5E6) WRITE (*,'(1X,A,G12.5,A)')
     &   'WARNING from SETPMD: Low short-wave radiation =',RDD,' J/m2/d'
      IF (WN.LT.0.2) WRITE (*,'(1X,A,G12.5,A)')
     &   'WARNING from SETPMD: Low wind speed =',WN,' m/s'

*     decide which calculation for long-wave radiation must be used
```

```
      IF (ANGA.EQ.0..AND.ANGB.EQ.0.) THEN
*        use Swinbank formula
         ILW = 1
      ELSE IF (ANGA.GT.0..AND.
     &         ANGB.GT.0..AND.
     &        (ANGA+ANGB).GT.0.5.AND.
     &        (ANGA+ANGB).LT.0.9) THEN
*        use Brunt formula
         ILW = 2
      ELSE
         CALL FATALERR ('SETPMD','illegal long-wave radiation option')
      END IF

      CALL SVPS1 (TMDA, VPS, VPSL)
      HUM = VP/VPS

      IF (HUM.GT.1.) THEN
         VPD = 0.
         IF (HUM.GT.1.4) WRITE (*,'(2A)') ' WARNING from SETPMD:',
     &      ' Vapour pressure more than 40% greater than saturated !'
      ELSE
         VPD = VPS-VP
      END IF

*     Long-wave radiation (J/m2/s and J/m2/d) and net radiation

      CALL SASTRO (IDOY,LAT,
     &             DUMR1,ANGOT,DUMR2,DUMR3,DUMR4,DUMR5,DUMR6,DUMR7)
      DATMTR = LIMIT (0.,1.,RDD/ANGOT)

      RDLOI = SIGMA*(TMDA+273.16)**4
      RDLO  = 86400.*RDLOI
      IF (ILW.EQ.1) THEN
*        Swinbank formula for net long-wave radiation
         RDLII = DATMTR*(5.31E-13*(TMDA+273.16)**6-RDLOI)/0.7+RDLOI
         RDLI  = 86400.*RDLII
      ELSE IF (ILW.EQ.2) THEN
*        Brunt formula for net long-wave radiation
         CLEAR = LIMIT (0., 1., (DATMTR-ANGA)/ANGB)
         RDLII = SIGMA*(TMDA+273.16)**4*(1.-(0.53-0.212*SQRT(VP))*
     &           (0.2+0.8*CLEAR))
         RDLI  = 86400.*RDLII
      END IF

      RDN = (1.-RF)*RDD+RDLI-RDLO

*     Wind functions and isothermal evaporation
*     2.63 is conversion from mm Hg to kPa

      IF (ISURF.EQ.1.OR.ISURF.EQ.2) THEN
```

```
*        open water and soils
         FU2 = 2.63*(0.5+0.54*WN)
      ELSE IF (ISURF.EQ.3) THEN
*        short grass crops
         FU2 = 2.63*(1.0+0.54*WN)
      ELSE
         CALL FATALERR ('SETPMD','unimplemented surface value')
      END IF

      EA = VPD*FU2

*     Actual water loss (separated in radiation term and
*     aerodynamic term) and resistance to transfer of vapour (s/m)
*     and estimated temperature difference

      ETRD = (RDN*(VPSL/(VPSL+PSCH)))/LHVAP
      ETAE = (PSCH*EA)/(VPSL+PSCH)
      ETD  = ETRD+ETAE
      RE   = 86400.*1000.*0.018016/(FU2*RBGL*(TMDA+273.16))
      DT   = RE*((RDN-LHVAP*ETD)/86400.)/RHOCP

*     Iteration on surface temperature if required with DO-WHILE loop

      IF (TMDI.GT.0.) THEN

         DTN    = 0.
         INLOOP = 0
         EQUIL  = .FALSE.
10       IF (INLOOP.EQ.0 .OR. .NOT.EQUIL) THEN
            DT = (DT+DTN)/2.

*           Net radiation and slope of saturated vapour pressure

            RDLOI = SIGMA*(TMDA+DT+273.16)**4
            RDLO  = 86400.*RDLOI
            RDN   = (1.-RF)*RDD+RDLI-RDLO
            CALL SVPS1 ((TMDA+DT), VPS2, DUMR1)
            VPSL = (VPS2-VPS)/DT

*           Actual water loss, resistance to vapour transfer and
*           estimated temperature difference

            ETRD = (RDN*(VPSL/(VPSL+PSCH)))/LHVAP
            ETAE = (PSCH*EA)/(VPSL+PSCH)
            ETD  = ETRD+ETAE
            RE   = 86400.*1000.*0.018016/
     &              (FU2*RBGL*(TMDA+0.5*DT+273.16))
            DTN  = RE*((RDN-LHVAP*ETD)/86400.)/RHOCP

*           Check on equilibrium and maximum number of iterations
```

```
      EQUIL  = ABS (DTN-DT).LT.TMDI
      INLOOP = INLOOP+1
      IF (INLOOP.GT.100.AND..NOT.EQUIL) CALL FATALERR
&         ('SETPMD','Cannot find equilibrium conditions')
      DT = DTN

   GOTO 10
   END IF
END IF

RETURN
END
```

Appendix II: Module SETPTD (Priestley-Taylor)

```
*----------------------------------------------------------------------*
* SUBROUTINE SETPTD (Subroutine Evap. Trans.Priestley-Taylor Daily)    *
* Authors: Daniel van Kraalingen                                       *
* Date   : 7-March-1997                                                *
* Version: 1.0                                                         *
* Purpose: This subroutine calculates reference evapotranspiration     *
*          in a manner similar to Priestley and Taylor (1972).         *
*          To obtain crop evapotranspiration, multiplication with a    *
*          crop factor should be done.                                 *
* Refs.  : Kraalingen, D.W.G. van, W. Stol, 1997. Evapotranspiration   *
*          modules for crop growth simulation. Quantitative Approaches *
*          in Systems Analysis No. 11. DLO Research Institute for      *
*          Agrobiology and Soil Fertility (AB-DLO), The C.T. de Wit    *
*          graduate school for Production Ecology (PE). Wageningen.    *
*          The Netherlands.                                            *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (units)                                    class *
* ----   ---- ---------------                                    ----- *
* IDOY    I4  Day number within year of simulation (d)              I  *
* LAT     R4  Latitude of site (dec.degr.)                          I  *
* RF      R4  Reflection (=albedo) of surface (-)                   I  *
* RDD     R4  Daily short-wave radiation (J.m-2.d)                  I  *
* TMDA    R4  24 hour average temperature (degrees C)               I  *
* ETD     R4  Potential evapotranspiration (mm.d-1)                 O  *
*                                                                      *
* Fatal error checks : none                                            *
* Warnings           : RDD < 0.5E6                                     *
* Subprograms called : SASTRO, SVPS1                                   *
* Required libraries : TTUTIL                                          *
* File usage         : none                                            *
*----------------------------------------------------------------------*
      SUBROUTINE SETPTD (IDOY,LAT,RF,RDD,TMDA,ETD)
      IMPLICIT NONE

*     Formal parameters
      INTEGER IDOY
      REAL LAT,RF,RDD,TMDA,ETD

*     Local variables
      REAL LHVAP,PSCH,SIGMA,PTFAC,VPSL,ANGOT,DATMTR,LIMIT
      REAL RDLOI,RDLO,RDLII,RDLI,RDN
      REAL DUMR1,DUMR2,DUMR3,DUMR4,DUMR5,DUMR6,DUMR7

      PARAMETER (LHVAP = 2454.E3 , PSCH  = 0.067, SIGMA = 5.668E-8)
      PARAMETER (PTFAC = 1.42)
```

```
      SAVE

*     Checks
      IF (RDD.LT.0.5E6) WRITE (*,'(1X,A,G12.5,A)')
     &   'WARNING from SETPTD: Low short-wave radiation =',RDD,' J/m2/d'

      CALL SVPS1 (TMDA, DUMR1, VPSL)

*     Long-wave radiation (J/m2/s and J/m2/d) and net radiation
*     according to Swinbank

      CALL SASTRO (IDOY,LAT,
     &             DUMR1,ANGOT,DUMR2,DUMR3,DUMR4,DUMR5,DUMR6,DUMR7)
      DATMTR = LIMIT (0.,1.,RDD/ANGOT)

      RDLOI = SIGMA*(TMDA+273.16)**4
      RDLII = DATMTR*(5.31E-13*(TMDA+273.16)**6-RDLOI)/0.7+RDLOI
      RDLO  = 86400.*RDLOI
      RDLI  = 86400.*RDLII
      RDN   = (1.-RF)*RDD+RDLI-RDLO

*     Priestley and Taylor reference evapotranspiration
      ETD = PTFAC*(RDN*(VPSL/(VPSL+PSCH)))/LHVAP

      RETURN
      END
```

Appendix III: Module SETMKD (Makkink)

```
*----------------------------------------------------------------------*
* SUBROUTINE SETMKD (Subroutine Evap. Trans. MaKkink Daily)            *
* Authors: Daniel van Kraalingen                                       *
* Date   : 7-March-1997                                                *
* Version: 1.0                                                         *
* Purpose: This subroutine calculates reference evapotranspiration     *
*          according to Makkink (1957). To obtain crop evapo-          *
*          transpiration, multiplication with a Makkink crop factor    *
*          should be done. The use of this formula is basically limited*
*          to areas with large amounts of radiation                    *
* Refs.  : Kraalingen, D.W.G. van, W. Stol, 1997. Evapotranspiration   *
*          modules for crop growth simulation. Quantitative Approaches *
*          in Systems Analysis No. 11. DLO Research Institute for      *
*          Agrobiology and Soil Fertility (AB-DLO), The C.T. de Wit    *
*          graduate school for Production Ecology (PE). Wageningen.    *
*          The Netherlands.                                            *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning (units)                                    class *
* ----   ---- ---------------                                    ----- *
* RDD     R4  Daily short-wave radiation (J.m-2.d)                 I   *
* TMDA    R4  24 hour average temperature (degrees C)              I   *
* ETD     R4  Potential evapotranspiration (mm.d-1)                O   *
*                                                                      *
* Fatal error checks : none                                            *
* Warnings           : RDD < 0.5E6                                     *
* Subprograms called : SVPS1                                           *
* Required libraries : none                                            *
* File usage         : none                                            *
*----------------------------------------------------------------------*
      SUBROUTINE SETMKD (RDD, TMDA, ETD)
      IMPLICIT NONE

*     Formal parameters
      REAL RDD, TMDA, ETD

*     Local variables
      REAL LHVAP, PSCH, VPS, VPSL, MAKFAC

      PARAMETER (LHVAP  = 2454.E3, PSCH = 0.067)
      PARAMETER (MAKFAC = 0.63)
      SAVE

*     Checks
      IF (RDD.LT.0.5E6) WRITE (*,'(1X,A,G12.5,A)')
     &   'WARNING from SETMKD: Low short-wave radiation =',RDD,' J/m2/d'
```

```
*       Calculate saturated vapour pressure
        CALL SVPS1 (TMDA, VPS, VPSL)

*       Calculate Makkink evaporation, MAKFAC factor is calibrated for the
*       Netherlands
        ETD = MAKFAC*(RDD*(VPSL/(VPSL+PSCH)))/LHVAP

        RETURN
        END
```

Appendix IV: Additional modules SASTRO, SVPS1

```
*----------------------------------------------------------------------*
* SUBROUTINE SASTRO                                                    *
* Authors: Daniel van Kraalingen                                       *
* Date   : 12-June-1996, Version: 1.1                                  *
* Purpose: This subroutine calculates solar constant, daily           *
*          extraterrestrial radiation, daylength and some intermediate *
*          variables required by other routines. The routine has been  *
*          written such that latitudes from pole to pole can be used.  *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning                                    units  class *
* ----   ---- -------                                    -----  ----- *
* IDOY    I4  Day of year (Jan 1st = 1)                    d      I   *
* LAT     R4  Latitude of the site                      degrees   I   *
* SOLCON  R4  Solar constant at day=IDOY                  W/m2    O   *
* ANGOT   R4  Daily extraterrestrial radiation           J/m2/d   O   *
* DAYL    R4  Astronomical daylength (base = 0 degrees)    h      O   *
* DAYLP   R4  Photoperiodic daylength (base = -4 degrees)  h      O   *
* DSINB   R4  Daily total of sine of solar height          s      O   *
* DSINBE  R4  Daily integral of sine of solar height       s      O   *
*             corrected for lower transmission at low              *
*             elevation                                            *
* SINLD   R4  Intermediate variable for subroutine SSKYC   -      O   *
* COSLD   R4  Intermediate variable for subroutine SSKYC   -      O   *
*                                                                      *
* Fatal error checks: LAT > 90, LAT < -90                              *
* Warnings          : LAT above polar circle, LAT within polar circle  *
* Required libraries: TTUTIL                                           *
* File usage        : none                                             *
*----------------------------------------------------------------------*

      SUBROUTINE SASTRO (IDOY   , LAT    ,
     &                   SOLCON, ANGOT , DAYL , DAYLP,
     &                   DSINB , DSINBE, SINLD, COSLD)
      IMPLICIT NONE

*     Formal parameters
      REAL LAT, SOLCON, ANGOT, DAYL, DAYLP, DSINB, DSINBE, SINLD, COSLD
      INTEGER IDOY

*     Local parameters
      REAL AOB, PI, DEGTRAD, DOY, DEC, ZZCOS, ZZSIN, ZZA
      SAVE

*     PI and conversion factor from degrees to radians
      PARAMETER (PI=3.1415927, DEGTRAD=0.017453292)
```

```
*     Error check and conversion of day number
      IF (ABS (LAT).GT.90.) CALL FATALERR
     &   ('SASTRO','LAT > 90 or LAT < -90')
      DOY = REAL (IDOY)

*     Declination of the sun as a function of daynumber,
*     calculation of daylength from intermediate variables
*     SINLD, COSLD and AOB

      DEC   = -ASIN (SIN (23.45*DEGTRAD)*COS (2.*PI*(DOY+10.)/365.))
      SINLD = SIN (DEGTRAD*LAT)*SIN (DEC)
      COSLD = COS (DEGTRAD*LAT)*COS (DEC)
      AOB   = SINLD/COSLD

      IF (AOB.LT.-1.) THEN
         WRITE (*,'(2A)') ' WARNING from SASTRO: ',
     &          'latitude above polar circle, daylength=0 hours'
         DAYL  = 0.
         ZZCOS = 0.
         ZZSIN = 1.
      ELSE IF (AOB.GT.1.) THEN
         WRITE (*,'(2A)') ' WARNING from SASTRO: ',
     &          'latitude within polar circle, daylength=24 hours'
         DAYL  = 24.
         ZZCOS =  0.
         ZZSIN = -1.
      ELSE
         DAYL  = 12.*(1.+2.*ASIN (AOB)/PI)
         DAYLP = 12.0*(1.+2.*ASIN ((-SIN(-4.*DEGTRAD)+SINLD)/COSLD)/PI)
         ZZA   = PI*(12.+DAYL)/24.
         ZZCOS = COS (ZZA)
         ZZSIN = SIN (ZZA)
      END IF

*     Daily integral of sine of solar height (DSINB) with a
*     correction for lower atmospheric transmission at lower solar
*     elevations (DSINBE)

      DSINB  = 2.*3600.*(DAYL*0.5*SINLD-12.*COSLD*ZZCOS/PI)
      DSINBE = 2.*3600.*(DAYL*(0.5*SINLD+0.2*SINLD**2+0.1*COSLD**2)-
     &         (12.*COSLD*ZZCOS+9.6*SINLD*COSLD*ZZCOS+
     &         2.4*COSLD**2*ZZCOS*ZZSIN)/PI)

*     Solar constant and daily extraterrestrial radiation
      SOLCON = 1370.*(1.+0.033*COS (2.*PI*DOY/365.))
      ANGOT  = SOLCON*DSINB

      RETURN
      END
```

```
*----------------------------------------------------------------------*
* SUBROUTINE SVPS1 (Subroutine Vapour Pressure Saturated no. 1)        *
* Authors: Daniel van Kraalingen                                       *
* Date   : 3-Feb-1991, Version: 1.0                                    *
* Purpose: This subroutine calculates saturated vapour pressure and    *
*          slope of saturated vapour pressure. Parameters of the       *
*          formula were fitted on the Goff-Gratch formula used in the  *
*          Smithsonian Handbook of Meteorological Tables. The          *
*          saturated vapour following the Goff-Gratch formula is also  *
*          available as a subroutine. (Note that 1kPa = 10 mbar)       *
*                                                                      *
* FORMAL PARAMETERS:  (I=input,O=output,C=control,IN=init,T=time)      *
* name   type meaning                                    units  class *
* ----   ---- -------                                    -----  ----- *
* TMA     R4  Temperature at which to calculate pressure    C       I  *
* VPS     R4  Saturated vapour pressure                    kPa      O  *
* VPSL    R4  Slope of VPS at TMA                          kPa/C    O  *
*                                                                      *
* Fatal error checks: none                                             *
* Warnings          : TMA < -20, TMA > 50                              *
* Subprograms called: none                                             *
* File usage        : none                                             *
*----------------------------------------------------------------------*

      SUBROUTINE SVPS1 (TMA,VPS,VPSL)
      IMPLICIT NONE
      REAL TMA,VPS,VPSL
      SAVE

      IF (TMA.LT.-20..OR.TMA.GT.50.) WRITE (*,'(A,G12.5,A)')
     &   ' WARNING from SVPS1: extreme temperature:',TMA,' d. Celsius'

      VPS  = 0.1*6.10588*EXP (17.32491*TMA/(TMA+238.102))
      VPSL = 238.102*17.32491*VPS/(TMA+238.102)**2

      RETURN
      END
```