PRELIMINARY REVIEW OF REVISED FAO RADIATION AND TEMPERATURE METHODS

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Abbreviations

PET = Potential evapotranspiration [mm/d]
PM = Penman-Monteith
RADEXT = Extended Radiation Method (Eq. (1))
RADSTA = Standardized Radiation Method
RADSIM = Simplified Radiation Method
RADORI = Original FAO Radiation Method
RADPRI = Priestley-Taylor Method
SEE = Standard error of estimate (Eq. (35))
TEMEXT = Extended Temperature Method
TEMSTA = Standardized Temperature Method
TEMSIM = Simplified Temperature Method
TEMHAR = Hargreaves Method

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1. Introduction

This research report has been written on request of the Food and Agricultural Organization (FAO) of the United Nations. The investigations conducted are meant as supporting material in the framework of reviewing the methods for estimating reference evapotranspiration as described in FAO Irrigation and Drainage Paper No. 24 (Crop Water Requirements, 1977).
This investigation was, among other studies, proposed by the 'Expert Consultation on Procedures for Revision of FAO Guidelines for Prediction of Crop Water Requirements', May, 1990. (From now on referred to as FAO Expert Consultation).

The results listed in this report are mainly based on the terms of reference of contract nr. 5484. They are grounded on the conclusions of the experts convening in the above mentioned FAO Consultation.
The terms of reference will be given after the theory underlying these conclusions.
The computer programs listed in the Appendices are meant for internal use only.

1.1. The Proposed Combination Equation.

The newly developed Combination equation, which resulted from the Expert Consultation, is based on a Penman-Monteith approach;

$$ET_o = \underbrace{\frac{\delta}{\delta+\gamma^*} * (R_n - G)\frac{1}{\lambda}}_{\text{Radiation term}} + \underbrace{\frac{\gamma}{\delta+\gamma^*} * \frac{936}{(T_{avg}+276)} * U_2 * (e_a - e_d)}_{\text{Aerodynamic term}} \qquad (1)^*$$

ET_o	: Reference crop evapotranspiration [mm/d]
R_n	: Net radiation at crop surface [MJ/m^2.d]
G	: Soil heat flux [MJ/m^2.d] =0 for time periods > 10-30 days
T_{avg}	: Average temperature [°C]
U_2	: Windspeed measured at 2 m [m/s]
(e_a-e_d)	: Vapour pressure deficit [kPa]
δ	: Slope of vapour pressure curve [kPa/°C]
λ	: Latent heat of vaporization [MJ/kg]
γ	: Adiabatic psychrometric constant [kPa/°C]
γ^*	: Modified psychrometric constant * [kPa/°C]

*This formula was taken from one of the preliminary reports underlying this investigation. In the final formula the values of 936 and 276 will be replaced by 925 and 273, respectively. The modifications are however of minor influence on the evaporation results.

Net radiation is composed of two parts: net shortwave and net longwave radiation: $R_n = R_{ns} - R_{nl}$.
Net shortwave radiation can be described by

$$R_{ns} = (1-\alpha) * R_s \qquad (2)$$

with

R_{ns}	: Net shortwave radiation [MJ/m².d]
α	: Canopy reflection coefficient = 0.23 overall average for grass
R_s	: Incoming solar radiation [MJ/m².d]

The incoming solar radiation is not measured but given by

$$R_s = (a_{sn} + b_{sn} \frac{n}{N})*R_a \qquad (3)$$

R_s	: Incoming solar radiation [MJ/m².d]
a_{sn}	: Fraction of radiation on overcast days = 0.25 for average climate
b_{sn}	: Fraction of additional radiation on clear days = 0.50 for average climate.
n/N	: Relative sunshine fraction
n	: Bright sunshine hours per day [hr]
N	: total daylength [hr]
R_a	: Extra terrestial radiation [MJ/m².d]

Whereas net longwave radiation is presented by Eq.(4).

$$R_{nl} = (0.9 \frac{n}{N}+0.1)*(0.34-0.139\sqrt{e_d})*\sigma*0.5*(T_{max}{}^4+T_{min}{}^4) \qquad (4)$$

R_{nl}	: Net longwave radiation [MJ/m².d]
e_d	: Dew point vapour pressure [kPa]
T_{max}	: Maximum temperature [K]
T_{min}	: Minimum temperature [K]
σ	: Stefan Boltzman constant [MJ/m².K⁴.d] = $4.903*10^{-9}$

If a temperature dependent emissivity correlation should be applied, the term $(0.34-0.139\sqrt{e_d})$ has to be replaced by the so-called Idso Jackson Equation:

$$\epsilon = -0.02 + 0.261 \exp(-7.77*10^{-4} * T_{avg}{}^2) \qquad (5)$$

T_{avg}	: Average daily temperature [°C]

The extraterrestial radiation, R_a, can be calculated from the following formulas as given in Smith, 1991.

$$R_a = 37.586*D_r*(\Omega*SIN(\Phi)*SIN(\delta)+COS(\Phi)*COS(\delta)*SIN(\Omega)) \qquad (6)$$

Where;

Φ	$= (\theta/360)*2*3.1416$	(7)
J	$= 30.42*MO-15.23$	(8)
D_r	$= 1 + 0.033 * COS(((2\pi)/365)*J)$	(9)
δ	$= 0.4093*SIN(((2\pi)*(284+J))/365)$	(10)
Ω	$= ARCCOS(COS(-TAN(\Phi)*TAN(\delta))$	(11)

In which;

D_r : Relative distance from earth to sun [rad]
Ω : Sunset hour angle [rad]
Φ : Latitude in radians [rad]
θ : Latitude in degrees [deg]
δ : Solar declination [rad]
J : Day of Year (DOY), integer value which represents the center of each month
MO : Month number

The vapour pressure deficit in the aerodynamic term is e_a-e_d , where

e_a : Saturation vapour pressure [kPa]
e_d : Actual vapour pressure, being the saturation vapour pressure at dewpoint [kPa]

The quantity e_a at average temperature is defined as the average of formula 12 calculated for both T_{min} and T_{max}.

$$e_a(T_{min},T_{max}) = 0.6108 * \exp\left(\frac{17.27*T}{T+237.3}\right) \qquad (12)$$

$$e_a(T_{avg}) = (e_a(T_{min})+e_a(T_{max}))/2$$

Where dewpoint data are available;

$$e_d = 0.6108 * \exp\left(\frac{17.27*T_{min}}{T_{min}+237.3}\right)$$

Otherwise e_d is obtained as:

$$e_d = e_a * (RH_{avg} /100) \qquad (13)$$

Where

T_{avg} : Average temperature, $(T_{max}-T_{min})/2$ [°C]
RH_{avg} : Average daily relative humidity [%]

Sometimes measurements or estimations of relative humidity are not available. The fact, however, that minimum temperature often approaches dewpoint temperature provides us with an expression derived from Eq. (12):

$$e_d = C_f * \exp\left(\frac{17.27 * T_{min}}{T_{min} + 237.3} \right) \tag{14}$$

The coefficient C_f is determined by the climate type in which the meteorological station is situated. For humid, temperate climates the value of 0.6108 is adequate, in more arid regions C_f will be usually lower. More information on the value of C_f will be given in Sections 2.4, 2.4.2, 2.4.4, 2.4.5, and 3.3.

The weighting terms $\delta/\delta+\gamma^*$ and $\gamma/\delta+\gamma^*$ in front of the radiation and aerodynamic terms of Eq. (1) consist of γ, γ^* and δ. These variables are defined in the following way.

The adiabatic psychrometric constant, γ:

$$\gamma = 1.63 * 10^{-3} * \frac{P}{\lambda} \tag{15}$$

P	: Atmospheric pressure [kPa]
λ	: Latent heat [MJ/kg] = 2.45

The modified psychrometric constant, γ^*:

$$\gamma^* = \gamma(1 + 0.347 * U_2) \tag{16}$$

The slope of the vapour pressure curve, δ:

$$\delta = \frac{4098 * e_a(T_{avg})}{(T_{avg} + 237.3)^2} \tag{17}$$

1.2. Description of New Radiation Method and Other Selected Radiation Equations.

Equation (1) has to be considered as the pivot on which the Revision hinges. This newly developed combination equation, based on the Penman-Monteith approach, provides the basis for revision of the FAO Radiation and Temperature Methods which will replace the original Radiation and Temperature Methods as given in Doorenbos and Pruitt (1977).
The reviewed Radiation and Temperature Method will not be a radiation and temperature method in the true sense of the word. This is caused by the fact that in both methods none of the 8 variables of Eq. (1) is neglected, and thus they should be adressed to as combination methods.

The fact however that certain components of Eq. (1) are standardized or empirically related to easily-available parameters, which makes that formula (1) needs either **global radiation** or **maximum and minimum temperatures** as maximum required **measured** input, has led to the appellation in terms of **Radiation and Temperature Method**.

The Original FAO Radiation and Temperature Methods (I&D-paper No. 24) have the same characteristic: although they are denominated as Radiation and Temperature Method, they need additional **estimates** of humidity, wind and relative sunshine fraction.

In the line of the terms of reference to be given in Section 1.4., the **new** FAO Radiation Method is considered in the following three ways.

1. The extended version (= PM-combination method, formula 1)
2. The standardized version
3. The simplified version

Ad.1. The **extended** version refers to equation (1), which considers ***measured*** values of global *radiation*, relative sunshine fraction (to calculate longwave radiation), average temperature (additionally needed to calculate e_a), windspeed, and actual vapour pressure.

Ad.2. The **standardized** version is related to Section 2.2 , which summarizes windspeed and mean relative humidity in several classes.
So besides knowledge of R_s, n/N, T_{max} and T_{min}, this time only ***estimates*** of U_2 and e_d (by Eq. (13)) are asked for.

Ad.3. Finally, the **simplified** version makes use of measured T_{max} and T_{min}, R_s and n/N values. Windspeed is divided into 4 classes. Vapour pressure is estimated from a measured parameter.

For the purpose of comparison, two other radiation equations were selected; the original FAO Radiation method, and the Priestley-Taylor equation, respectively. They will be summarized below.

The original FAO Radiation Method:

The relationship between ET_o and several meteorological parameters is given by;

$$ET_o = (c*(W*Rs))/2.45 \qquad (18)$$

Where:

ET_o	: Reference crop evapotranspiration for the period considered [MJ/m^2.d]
R_s	: Solar radiation [MJ/m^2.d]
W	: Weighting factor depending on temperature and altitude
c	: Adjustment factor which depends on mean humidity and daytime wind conditions.
2.45	: Latent heat of vaporization [MJ/kg]

Calculation of ET_o will be done according to the relationships given in Section 1.1 which is based on Annex 1 of Pereira and Smith (1990).

Priestley-Taylor equation:

The Priestley-Taylor relationship is given by

$$ET_o = (\alpha \frac{\delta}{\delta+\gamma} (R_n - G))/2.45 \tag{19}$$

R_n : Net radiation $[MJ/m^2.d]$
G : Soil heat flux $[MJ/m^2.d]$

where $\alpha = 1.26$ when the general surrounding areas are wet or under humid conditions.

1.3. Description of New Temperature Method and Other (Radiation)-Temperature Equations.

The derivation of Temperature Methods from the Combination Equation 1 is based on standardization of the Radiation term.
In analogy with the reviewed Radiation method, the reviewed Temperature method was also calculated in various ways.

1. The extended version (Eq. (1) with ***estimated*** values of R_s)
2. The standardized version
3. The simplified version

Ad.1. The **extended** Temperature version equals Eq. (1), but it uses a standardized radiation term (3 classes of relative sunshine fraction, see Section 2.5)

Ad.2. The **standardized** version applies both the standardized radiation term as well as the standardized aerodynamic term.
(See ad.2 of Radiation Method).

Ad.3. In the **simplified** version actual vapour pressure and global incoming radiation are estimated.

In item B.6 of the Terms of Reference as they are listed in Section 1.4 it is recommended to test the validity of the revised Temperature method against the original FAO Temperature Method, the Hargreaves equation and the revised Radiation method.

The original FAO Temperature method is based on the Blaney-Criddle equation. The relationship is expressed as;

$$ET_o = (c\ [p(0.46T_{avg} + 8)])/2.45 \qquad (20)$$

where:

ET_o : Reference crop evapotranspiration for the month considered [MJ/m^2.d]

p : Mean daily percentage of total annual daytime hours for a given month and latitude.

c : Adjustment factor depending on minimum relative humidity, sunshine hours and daytime wind estimates.

A mathematical description for parameter p can be found in Jensen et al (1990). This method was not included in the 'computer-aided' comparison.

In fact, the **Hargreaves equation** is not a Temperature Method. It can be classed with the so-called Radiation-temperature methods, like the Jensen-Haise method or the Turc method, which uses incoming global radiation or calculated extra-terrestial radiation (in this case) as extra input.
It is defined by the following equation:

$$ET_o = (0.0023\ R_a * (T_{max}-T_{min})^{\frac{1}{2}} *(T_{avg} + 17.8))/2.45 \qquad (21)$$

Where:

R_a : The extraterrestial radiation [MJ/m^2.d]

1.4. Terms of Reference According to FAO.

A. Review of FAO Radiation Formula

1. Assuming the general validity of the Combination Method (Penman-Monteith), improve the radiation term by introducing longwave radiation.

2. For estimation of longwave radiation, use a temperature dependent emissivity correlation.

3. Simplify the aerodynamic term of the Combination Method for various climatic conditions by standardizing values for wind and vapour pressure deficit.

4. Elaborate with a set of climatic data on a possible correlation between vapour pressure deficit and $T_{max}-T_{min}$ values as a possible parameter to improve aerodynamic term estimates.

5. Propose practical correction factors for various climatic conditions with an indication of validity range.

6. Evaluate validity of revised Radiation versus original FAO Radiation Method and selected other radiation equations.

7. Prepare a short report on the results.

B. Review FAO Temperature Method.

1. Assuming the general validity of the Combination Method (Penman-Monteith), try to simplify the radiation term by standardized values for sunshine duration.

2. Elaborate with a set of climatic data on a possible correlation between sunshine duration and $T_{max}-T_{min}$, as a possible parameter to improve radiation term estimates.

3. Similarly, simplify the aerodynamic term for various climatic conditions by standardizing values for wind and vapour pressure deficit (see A.)

4. Elaborate with a set of climatic data on a possible correlation between vapour pressure deficit and $T_{max}-T_{min}$ values as a possible parameter to improve aerodynamic term estimates (see A.)

5. Propose a generalized form for the Temperature Method, using Tmax and Tmin data to estimate evapotranspiration, introducing a possible correction factor for various climatic conditions.

6. Test the validity of the revised Temperature Method versus original FAO Temperature Method, the Hargreaves equation and the revised Radiation method.

7. Prepare a short report on the results.

Chapter 2 will describe the standardization and simplification activities in the same order the Terms of Reference are given in.

1.5. Data Sets.

The data on which this investigation is based were mainly extracted from the agrometeorological data base of the FAO, which was provided by the Agrometeorology Group.
The data covered large parts of Europe, the Middle-East, Asia, Africa and South-America.
The FAO data were stored in 8 files, with the names PAR01, PAR02, PAR03, PAR04, PAR05, PAR07, PAR08, and PAR09.
They contained the following parameters.

PAR01 : Average monthly precipitation total [mm].
PAR02 : Mean monthly temperature [°C].
PAR03 : Mean monthly maximum temperature [°C].
PAR04 : Mean monthly minimum temperature [°C].

PAR05 : Mean monthly actual vapour pressure [mb].
PAR07 : Average monthly wind speed at 2 m above the surface [m/s].
PAR08 : Relative sunshine fraction [%], being the ratio of actual hours of bright sunshine (n) and daylength (N), which depends on date and latitude.
PAR09 : Global incoming radiation [cal/cm^2.d]. These data were calculated from the extraterrestial radiation R_a, the relative sunshine fraction (n/N) and Angström's coefficients a_{sn} and b_{sn} (see Eq. 3)
The parameters a_{sn} and b_{sn} are dependent on the prevailing climatic conditions. The following values were considered:

Climate	a_{sn}	b_{sn}
Arid, semi-arid	0.25	0.45
Tropical humid	0.29	0.42
Other	0.18	0.55

Reference: FAO

All data files had a similar structure. They contained 18 columns, separated by comma's.

Column 1 : WMO station number.
Column 2 : Weather element number.
Column 3 : Last three digits of first year of record.
Column 4 : Length of record used to compute the average value.
Column 5-16 : 12 monthly parameter values.
Column 17 : Undefined variable, sometimes the average value or the sum of the paramer values. In certain files the significance of this column was unclear.
Column 18 : A quoted string containing comments on the data.

Despite the impressive amount of data stored in these files, they had some disadvantages. For example, the format they were written in, the so-called 'comma-separated string' was rather inconvenient. In the first place, this format cannot be read by programs in Fortran. Secondly the data could not be scanned easily, as each row (representing a station number) had a different length.
Furthermore, the data per file were not stored in the same order of station number, which made reading of the files a very time-consuming affair. Sometimes station numbers and their respective data were missing in certain files.

To overcome these problems all data files were reorganized.
Superfluous information like weather element, first year of record, length of record, 'column 17' and the text-string were removed.
Furthermore all stations were arranged in the same order. Station numbers which were not covering all data files were deleted.

Data per file were put into the same format (integer or real), with a fixed blank between each monthly value, in order to facilitate survey of the files.

To run the programs developed for this investigation, the data of the reorganized files were applied. Mean monthly temperatures were calculated from mean minimum and mean maximum temperatures.
Global radiation in $cal/cm^2.d$ was transformed in $MJ/m^2.d$ by multiplication with 0.041868. Actual vapour pressure in mbar was changed to actual vapour pressure in kPa trough a division by 10.0.

This conversion finally resulted in 7 files; PAR01.DAT, PAR03.DAT, PAR04.DAT, PAR05.DAT, PAR07.DAT, PAR08.DAT and PAR09.DAT, with the numbers referring to the same weather elements as in the original files.

Besides information from the FAO data files, additional climatic data were taken from the CABO/TPE Weather System.
These data resulted from a joint effort of the Centre for Agrobiological Research and the Department of Theoretical Production Ecology of the Wageningen Agricultural University.
The CABO/TPE datasets contained daily values of relevant meteorological variables, in contrast with the FAO datasets which only supplied monthly values.

2. Review of the Radiation and Temperature Methods According to Terms of Reference.

2.1. Incorporation of Longwave Radiation and Temperature Dependent Emissivity Equation in the Radiation Term of Equation (1).

Eq. (1) with accessory formulas was built into a Fortran program. This program also contained the equations for the calculations of potential evapotranspiration with the other Radiation and Temperature methods.

The advantages of using a code-program instead of a worksheet are several. Fortran code can be used both on a personal computer as well as on a VAX-mainframe. Furthermore a Fortran program provides a clear survey of the equations used, with additional explanation. Changes by users can be easily made and interactive information exchange is possible.

By creating this program, point 1 and 2 of the 'Review of the Radiation formula' were automatically taken care of.
Listing of the source code is given in Appendix 1. The program has been made suitable for reading of the new data files.

2.2. Standardization of the Aerodynamic Term of Equation (1).

Standardization of the aerodynamic term of Eq. (1) to yield the standardized new Radiation Method can be done in a way similar to the one used in Section 1.2 of Doorenbos and Pruitt (1977).
The same four humidity classes (low, low-medium, medium-high, and high) can be applied.
To provide the user with the aerodynamic term, 4 auxiliary graphs can be depicted. An example of such a graph is given in Fig. 2.1. It gives the aerodynamic term without the weighting factor $\gamma/(\delta+\gamma^*)$ as a function of temperature only, provided it is known to which humidity and wind class the period under consideration belongs.

Additional tables can supply the weighting factors W1 and W2 ($\delta/(\delta+\gamma^*)$ and $\gamma/(\delta+\gamma^*)$, respectively) as a function of temperature, wind and height (See Table 2.1 as an example).

The programs calculating the uncorrected part of the aerodynamic term (AERO.FOR) and the weighting factors $\delta/(\delta+\gamma^*)$ and $\gamma/(\delta+\gamma^*)$ (DELGAM.FOR) with accessory inputfiles are given in Appendices 2 and 3, respectively.

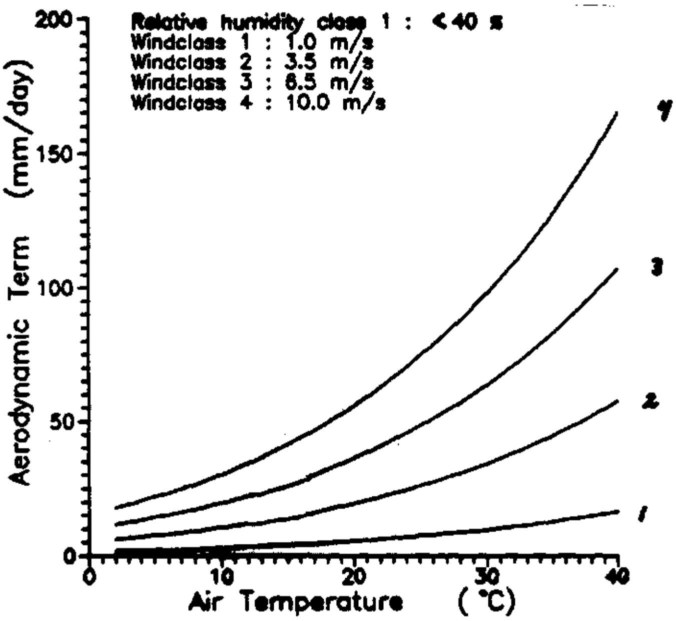


Fig. 2.1. **The aerodynamic term without the weighting factor** $\gamma/(\delta+\gamma^*)$ as a **function of the average air temperature** (T_{avg}), **for relative humidity class 1** and 4 windspeed options.

Table 2.1. Weighting factor $W1=\delta/(\delta+\gamma^{*})$ as a function of the average air temperature (T_{avg}) and altitude of the meteorological station. Windspeed is 3.5 m/s.

	Air Temperature (°C)																		
Height	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38
0	.36	.39	.42	.45	.48	.50	.53	.56	.59	.61	.64	.66	.69	.71	.73	.75	.77	.78	.80
250	.36	.39	.42	.45	.48	.51	.54	.57	.60	.62	.65	.67	.69	.71	.73	.75	.77	.79	.80
500	.37	.40	.43	.46	.49	.52	.55	.58	.60	.63	.65	.68	.70	.72	.74	.76	.78	.79	.81
750	.38	.41	.44	.47	.50	.53	.56	.58	.61	.64	.66	.68	.70	.73	.75	.76	.78	.80	.81
1000	.39	.42	.45	.48	.51	.54	.56	.59	.62	.64	.67	.69	.71	.73	.75	.77	.79	.80	.82
1500	.40	.43	.46	.49	.52	.55	.58	.61	.63	.66	.68	.70	.72	.74	.76	.78	.79	.81	.82
2000	.42	.45	.48	.51	.54	.57	.59	.62	.65	.67	.69	.71	.73	.75	.77	.79	.80	.82	.83
2500	.43	.46	.49	.52	.55	.58	.61	.63	.66	.68	.71	.73	.75	.76	.78	.80	.81	.83	.84
3000	.45	.48	.51	.54	.57	.60	.62	.65	.67	.70	.72	.74	.76	.78	.79	.81	.82	.84	.85
3500	.47	.50	.53	.56	.58	.61	.64	.66	.69	.71	.73	.75	.77	.79	.80	.82	.83	.84	.85
4000	.48	.51	.54	.57	.60	.63	.65	.68	.70	.72	.74	.76	.78	.80	.81	.83	.84	.85	.86

2.3. Simplification of the Aerodynamic Term of Equation (1).

2.3.1. Climatological Division.

Elaboration of points 4-6 of the Terms of Reference as given for the review of the Radiation method asks for a climatological classification. Sixteen classes were proposed by FAO, based on the following rainfall and temperature classes.

Rainfall		***Mean daily temperature***	
Humid	: > 150 mm/month	Hot	: > 25 °C
Subhumid	: 70-150 mm/month	Warm	: 20-25 °C
Semi-arid	: 20- 70 mm/month	Cool	: 10-20 °C
Arid	: 0- 20 mm/month	Cold	: < 10 °C

In this report the FAO recommended rainfall classes were applied.
However, shifting of the data into several climatological classes was not based on the **average temperature classes** as given above. This was decided mainly because average air temperature was not considered to be very suitable as distinctive parameter (e.g. both a monsoon and a desert climate can be characterized by temperatures > 25 °C, although they are of a completely different nature).

Besides, this kind of classification leads to curves covering a small data range, as most meteorological parameters (like for example E_a) are dependent on temperature.

Finally, basing a classification on a certain parameter (in this case T_{avg}) leads to the consequence that this parameter should not be used anymore as independent variable (x-value).

Furthermore, after careful examination of the meteorological dataset provided by FAO, it became clear that the variable $T_{max}-T_{min}$ is poorly correlated with other meteorological parameters. This is caused by the fact that in many climates $T_{max}-T_{min}$ stays more or less constant troughout the year. This statement is illustrated by Fig. 2.2.

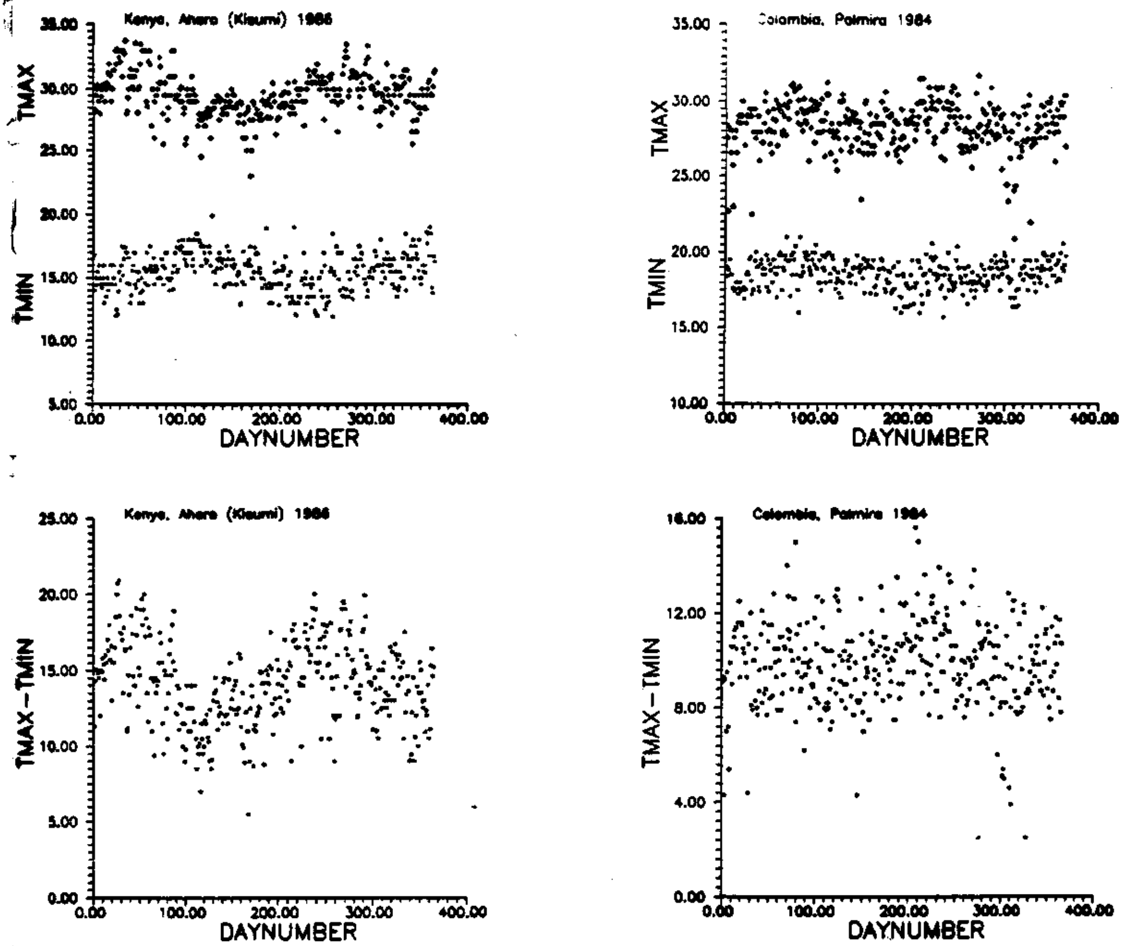


Fig. 2.2. Variation of maximum (T_{max}) and minimum (T_{min}) temperature and of the difference ($T_{max}-T_{min}$) with daynumber for meteorological stations in Kenya and Colombia, respectively.

These graphs were obtained by presenting graphically several data of the CABO/TPE Weather System. In contrast to the FAO Climatological dataset these measurements were taken on a daily basis. The figures, representing various climatic conditions, indicate that the $T_{max}-T_{min}$ value is changing very little during the year.

There are however also climates showing a clear seasonal oscillation of $T_{max}-T_{min}$ values. Climates with about the same average temperature (see Fig. 2.3, Israel versus Italy) will be put into the same climatological class, whereas they have substantially different $T_{max}-T_{min}$ values, and thus will not have identical relationships between this temperature difference and other meteorological parameters.

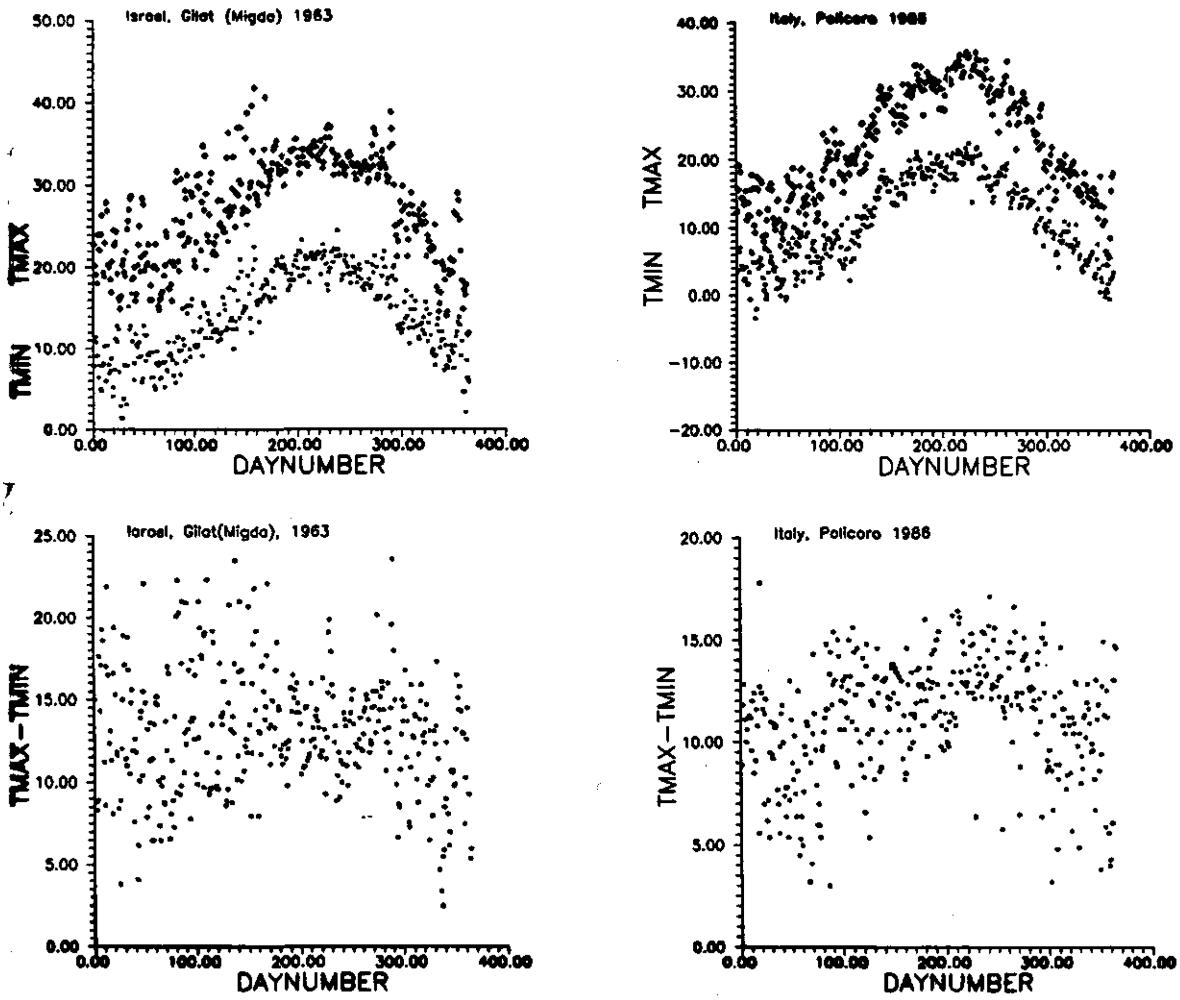


Fig. 2.3. Variation of maximum (T_{max}) and minimum (T_{min}) temperature, and the difference ($T_{max}-T_{min}$) with daynumber for meteorological stations in Israel and Italy, respectively.

Figs. 2.4–2.9 are yet another argument to abandon the idea of creating climatological classes based on average temperatures (and amounts of precipitation) and trying to relate $T_{max}-T_{min}$ to parameters like vapour pressure deficit or relative sunshine fraction as suggested in the Terms of Reference.

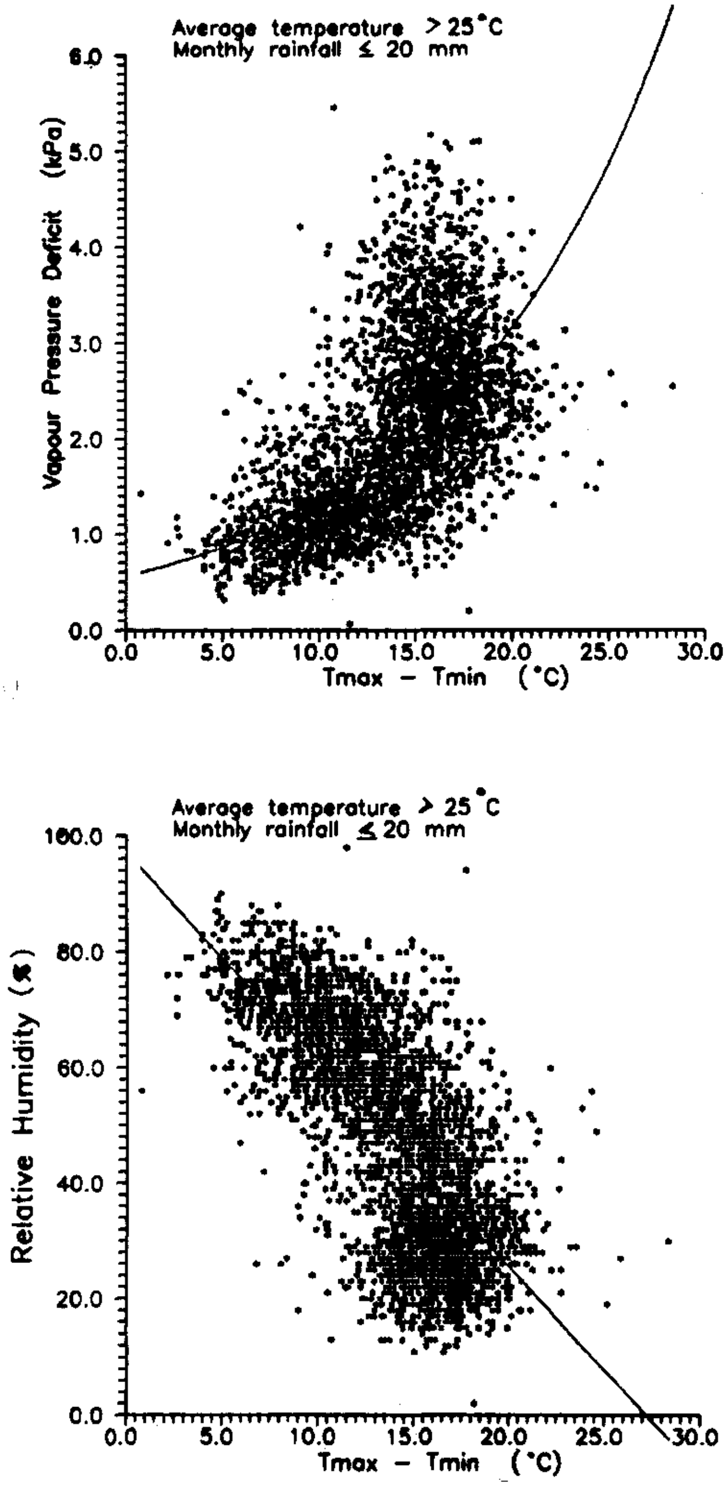
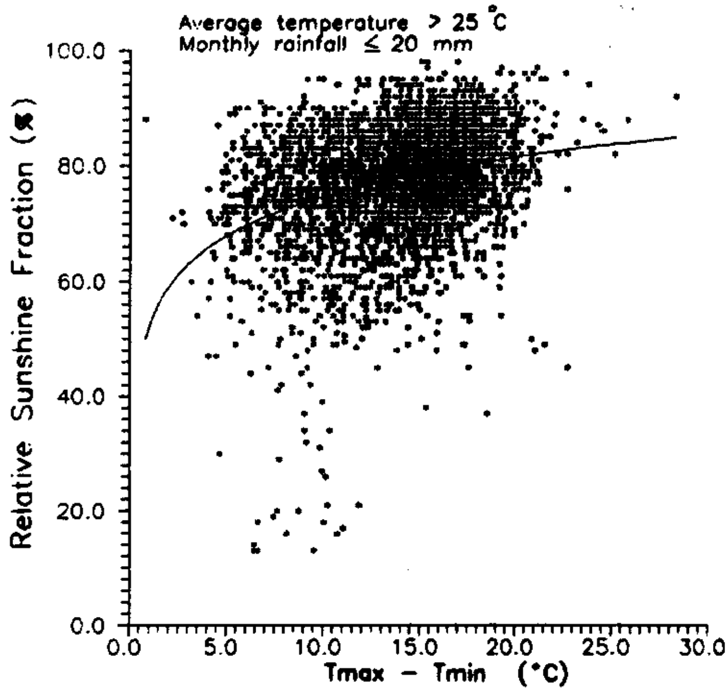


Fig. 2.4. Vapour pressure deficit (e_a-e_d) and relative humidity (RH) as a function of (T_{max}-T_{min}) for the arid-hot climate.



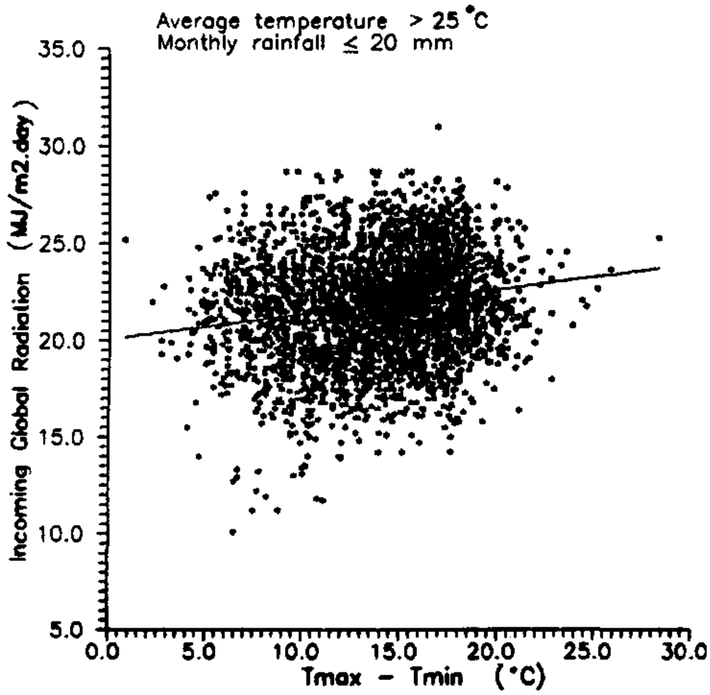
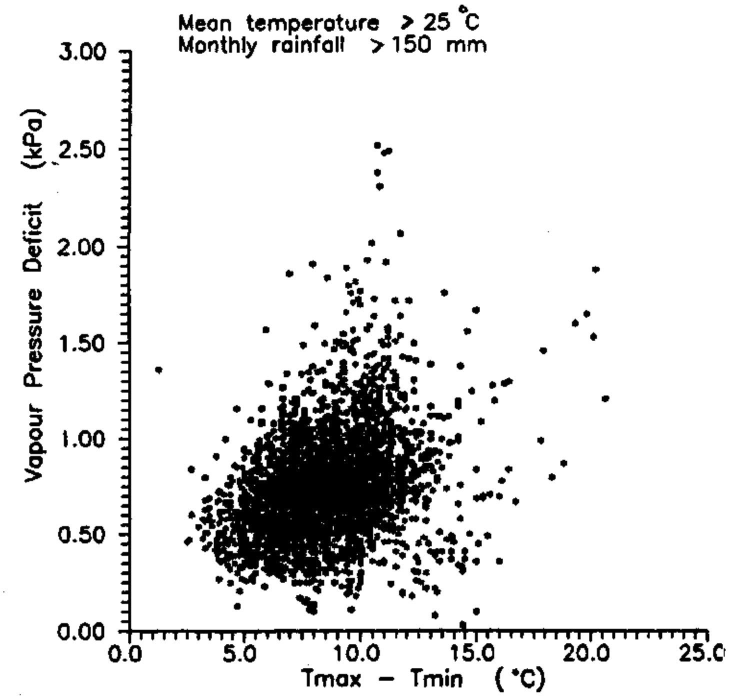


Fig.2.5. Relative sunshine fraction (n/N) and incoming global radiation (R_s) as a function of (T_{max}-T_{min}) for the arid-hot climate.



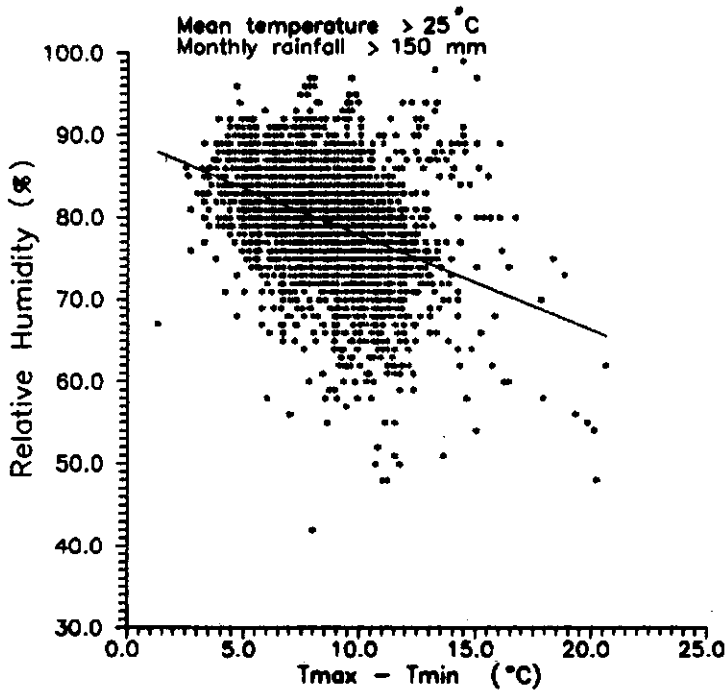


Fig. 2.6. Vapour pressure deficit (e_a−e_d) and relative humidity (RH) as a function of (T_{max}−T_{min}) for the humid-hot climate.

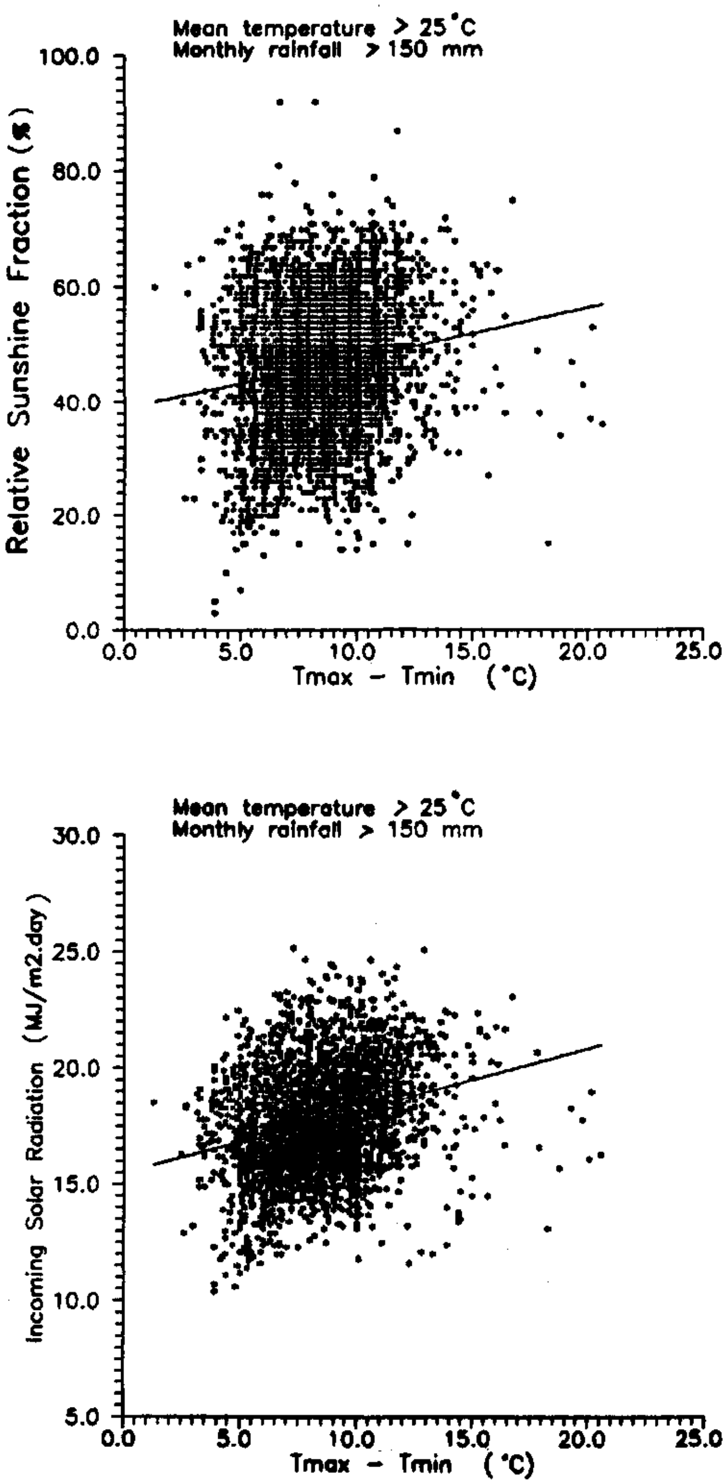
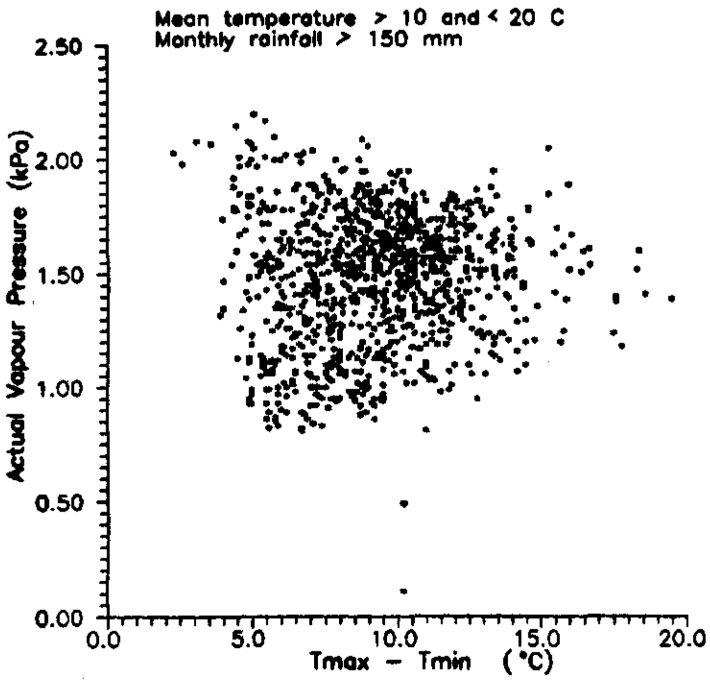


Fig. 2.7. Relative sunshine fraction (n/N) and incoming global radiation (R_s) as a function of (T_{max}–T_{min}) for the humid-hot climate.



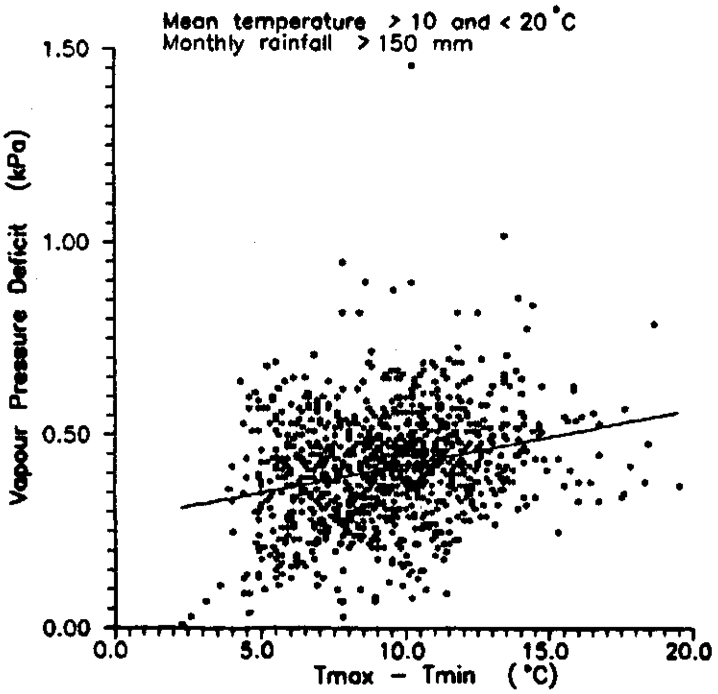


Fig. 2.8. Actual vapour pressure (e_d) and vapour pressure deficit (e_a-e_d) as a function of (T_{max}-T_{min}) for the humid-cool climate.

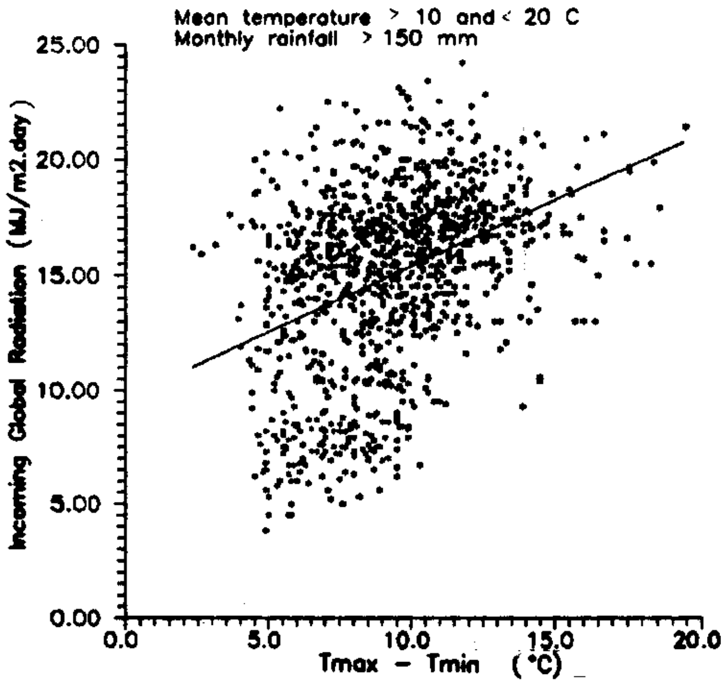


Fig. 2.9. **Variation of incoming global radiation (R_s) as a function of (T_{max}-T_{min}) for the humid-cool climate.**

Alternative classification

Despite the experiences summarized in Figs. 2.4–2.9 it was decided to divide the data into groups based on the value of (T_{max}–T_{min}).
This might seem contradictory, after the exposition given above. However, Figs. 2.4–2.9 are not included to deny the fact that values of (T_{max}–T_{min}) provide certain information about a climate. They are merely meant to indicate that it is not justified to correlate this parameter, divided into small intervals, with for example relative sunshine fraction.
Temperature difference (T_{max}–T_{min}) has to be considered as a sort of rough humidity indicator, like in the Hargreaves method.

This dependence of relative humidity on (T_{max}–T_{min}) can in fact be found in Figs. 2.4 and 2.6. However, this dependency is not unique enough to serve as a reliable estimate of vapour pressure deficit in Eq. (1). (Especially in the case of an arid climate).

Three classes were distinguished, based on monthly temperature difference. This was done as the FAO dataset only contained monthly values. Values of (T_{max}–T_{min}) were less than 15 ° C, between 15 and 20 °C and higher than 20 °C, respectively.
These three classes were each divided into the four recommended precipitation classes; arid, semi-arid, subhumid, and humid, respectively.
Table 2.2 gives a summary of the climates originating from this division, where A stands for arid, SA for semi-arid, SH for subhumid and H for humid.

Table 2.2. Climatological division applied in this report.

	Monthly precipitation class:			
Air Temp. Diff. [°C] (T_{max}–T_{min})	Arid ≤ 20 mm	Semi-arid 20–70 mm	Subhumid 70–150 mm	Humid ≥ 150 mm
< 15	A15	SA15	SH15	H15
15–20	A1520	SA1520	SH1520	H1520
> 20	A2040	SA2040	SH2040	H2040

On the basis of this divison the FAO-data, obtained all over the globe, were subdivided. This procedure led to the fact that for a certain meteorological station, for example, June belonged to class A15, wheras January was placed in SA1520. All months were joined, so no distinction was made between seasons (summer,winter).

2.4. Simplified Expressions for Actual Vapour Pressure

According to the Terms of Reference, the aerodynamic term of Eq. (1) had to be simplified and calibrated for various climatic conditions.
Because in many cases very few meteorological data are actually measured, a simple relationship between a moisture parameter and an easily available parameter had to be searched for. Two variables that are very often recorded are minimum and maximum air temperature.

It appeared that a clear relationship exists between minimum temperature and actual vapour pressure (both on monthly basis) for the various climatic groups. This fact was already acknowledged by numerous other authors. It is based on the knowledge that the dewpoint temperature (which determines the actual vapour pressure) in many climates lies very close to the minimum temperature.
This effort however is probably the first time that a relationship was searched for in extended climatological classes, and not for single locations only.

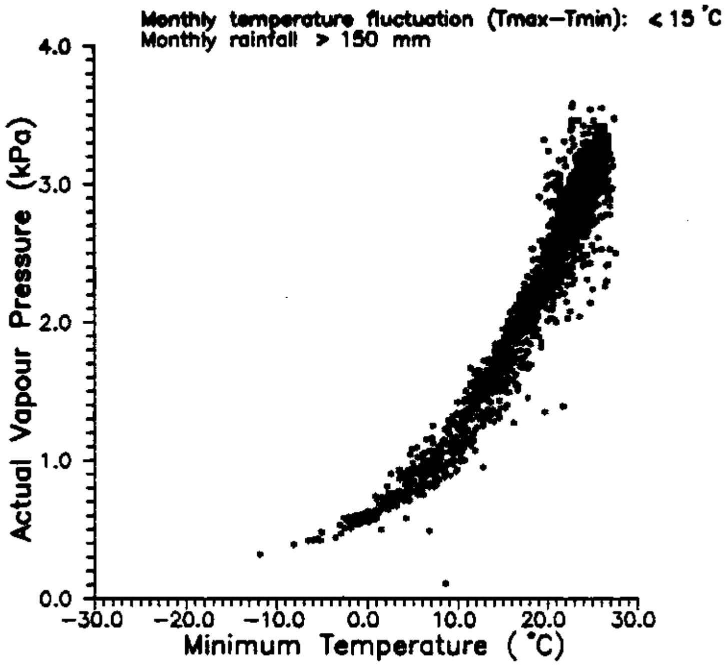
For arid and semi-arid regions, actual vapour pressure derived from minimum temperature (Eq. (14)) is diverging considerably from measured actual vapour pressure or from vapour pressure calculated from dewpoint temperature (Eq. (12) with T_{dew} used in stead of T_{avg}).
This phenomenon was recorded indeed for the (S)A15, (S)A1520, and (S)A2040 climates.

Fig. 2.10 is given as a graphical illustration of the abovementioned relationship between minimum temperature and actual vapour pressure. It appears that scatter is increasing considerably as climate becomes drier.

Conclusion: Eq. (14) works satisfactorily in describing actual vapour pressure for humid climates with small temperature differences (H15). For drier climates and climates with a (T_{max}-T_{min}) value of > 15°, however, application of this formula may cause larger deviations.
In these cases, individual equations derived for each Climate Class may be necessary.

In order to be able to relate all meteorological stations to one single formula however, it is recommendable to describe the 12 Climate Classes at the first place by Eq. (14).

It looks as if this approach will lead to the necessity of providing tables with coefficients (C_f) for each individual country or region.
This may be the price which has to be paid for the fact that only measurements of minimum temperature are needed to obtain humidity values.
This is due to the fact that it is definitely not possible to generalize specific areas, like coastal zones, deserts, or mountainous regions.
This because each region on earth is influenced by different ocean currents, prevailing winds, and climatic conditions.
A coastal area boarding the Atlantic Ocean will show properties differing completely from a coast which is sited in the Pacific.
For these reasons, even within a small continent like Europe, coefficients will already vary considerably.



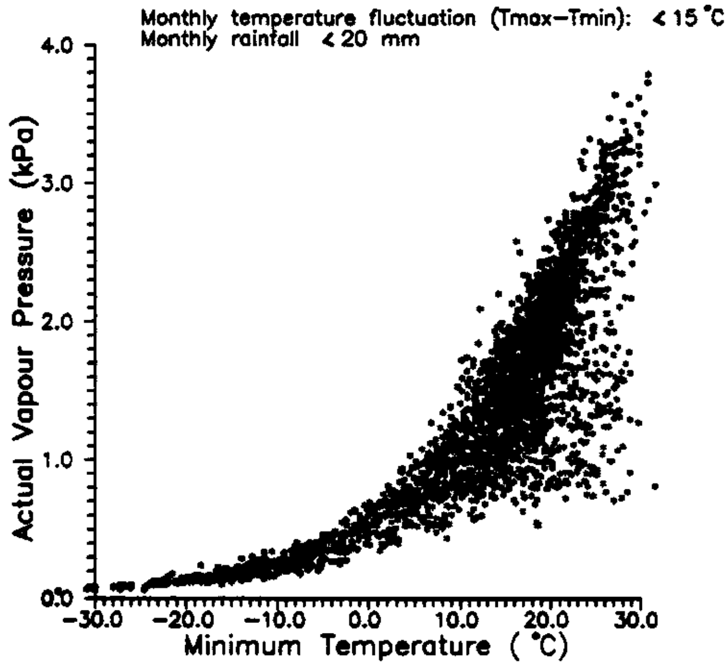


Fig. 2.10. **The relationship between minimum air temperature (T_{min})** and actual vapour pressure (e_d) for a humid and an arid climate, respectively.

Determination of coefficient, C_f

In order to find the coefficients needed to derive a proper value of actual vapour pressure from minimum temperature only, a simple program was developed. For every Climate Class it reads minimum temperature and measured actual vapour pressure from PAR04.DAT and PAR05.DAT, respectively.
Assuming that the relationship between minimum temperature and actual vapour pressure can be described by the exponental function given in Eq. (14), it provides for every station (and accessory month) falling into this climate class the coefficient with which this formula has to be multiplied.
For the humid and subhumid areas this factor will be close to 0.61, for the arid areas it can be as low as 0.10 for individual stations.

Calculating these coefficients for all countries described by the stations supplied by the FAO data set is a tremendous job and certainly falls beyond the scope of this investigation.

The coefficients were thus only calculated for a few Climate Classes, to serve as an illustration of possible variability.
This was done because the data sets (especially the arid ones) are very extensive.

Finding proper coefficients was hampered by the fact that the stations were described by their longitude and latitude only. Location of the stations by an ordinary atlas was therefore rather inconvenient, as most of them were not indicated on the maps.

Collection of the coefficients in a FAO-publication might be one of the options. It will be, however, a very tedious job and it might suggest an exactness which will be very tricky, as even within the different coefficients for one country or region a considerable variation still exists.

Relations between C_f and meteorological parameters

Because it appears that determination of the coefficients is very time-consuming, it was figured out if a relationship existed between these coefficients and certain meteorological parameters.
Between the minimum temperature and the overall coefficient a very rough relationship appeared to exist. However, for the more humid climates this relationship was considered not to be unique enough to describe the coefficients properly.
For this reason this relationship was only applied in case of the arid climates (A15, A1520, and A2040). See Fig. 2.11 as an example.

Furthermore, an attempt was made to relate the slope of the actual vapour pressure curve (δ) to, for example, minimum temperature, Tmax-Tmin, rainfall amount etc. This because knowledge of δ leads immediately to the actual vapour pressure, as δ is the derivative of the vapour pressure curve. ($y = a*e^b$ gives $y' = ab*e^b$ and thus $y/y'=b$, See Fig. 2.12).
No proper relationships occurred.

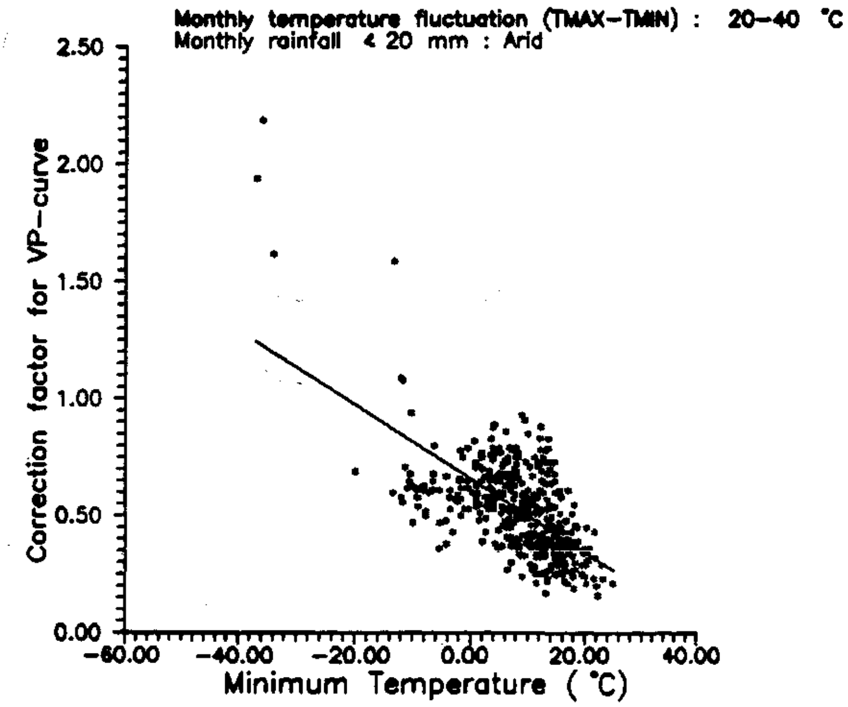


Fig. 2.11. Overall coefficient (C_f) for the actual vapour pressure (e_d) as a function of minimum temperature (T_{min}).

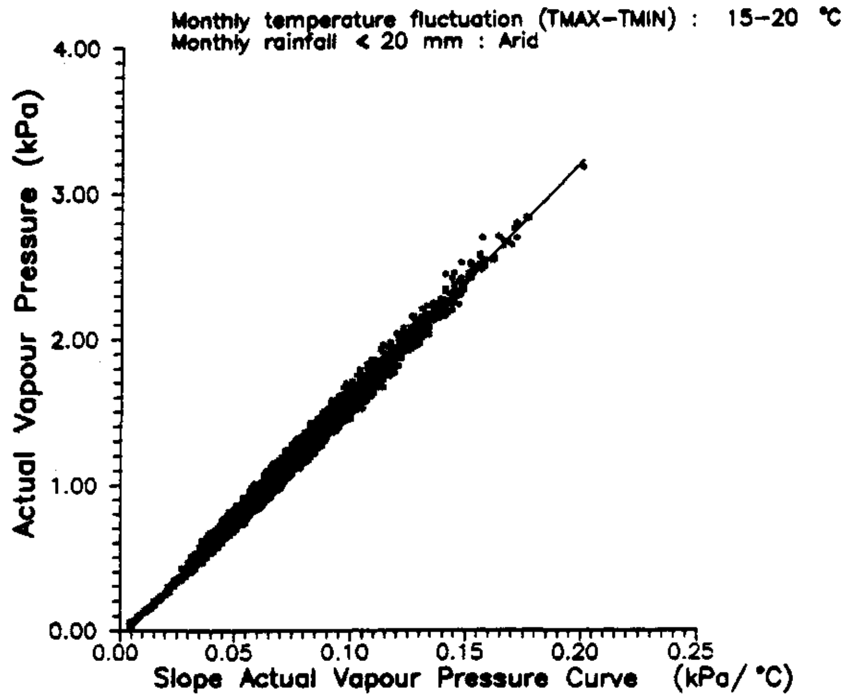


Fig. 2.12. The relationship between actual vapour pressure (e_d) and it's derivative, i.e. the slope of the vapour pressure curve, δ.

This leaves us again with the problem of determination of the coefficients.

Because determination of the numerous amount of coefficients seems unfeasible, only four coefficients were used in the evaluation of the various selected methods. Their values are:

Humid	$C_f = 0.61$
Subhumid	$C_f = 0.61$
Semi-arid	$C_f = 0.55$
Arid	$C_f = f(T_{min})$

Furthermore, because actual vapour pressure is only one of the various parameters determining potential evapotranpiration, it might well be that the accuracy of actual vapour pressure we are aiming at might be somewhat overdone. For this reason, the use of constant coefficients per climate class (based on rainfall only !) to be used in the comparative analysis of the several evaporation methods, seems justified.

Alternative equations

To give extra information, empirical exponential relationships between minimum temperature and actual vapour pressure were derived for each individual climate.
Whereas for the humid climates one equation combined with a few coefficients will be sufficient to describe all data points, the more arid climates needed many coefficients, mainly based on the location of the stations (coastal zone, desert area, island, high elevations, etc.).

Even with these subdivisions, scatter of the data around the derived curves remained large and showed that arid areas have a non-unique physical behaviour which makes it very difficult to cover these areas by simple relationships.

In the Sections 2.4.1-2.4.12 the various Climate Classes will be summarized by their relationship between minimum temperature and actual vapour pressure (by equations particularly referring to the individual Climate Classes).
Possible practical coefficients for deviating conditions will be given for some Climate Classes.
Additionally, some salient features for each climate are listed. They are given as the maximum possible data range for several important parameters of Eq. (1).

2.4.1. Humid, T_{max}-T_{min}: < 15 ° C

This class shows a considerably uniform behaviour. The individual relationship between minimum temperature and actual vapour pressure can be described by the following equation.

$$e_d = 0.673 * \exp(0.0626 * T_{min}) \qquad (22)$$

Where;

e_d : Average monthly actual vapour pressure [kPa].
T_{min} : Average monthly minimum temperature [°C].

A summary of this climate by possible parameter ranges is given below in Table 2.3.

Table 2.3. Parameter ranges of the H15 climate.

	T_{max}	T_{min}	RH	R_s	n/N
	°C	°C	%	Mj/m².d	%
Min. Value	-4	-13	50	2	10
Max. Value	38	28	100	25	75

Fig. 2.10 shows the graphical representation of the relation between minimum temperature and actual vapour pressure. Because this climate is humid, not many datapoints are deviating. As already said, this is caused by the fact that minimum temperature in these cases is lies close to dewpoint temperature.

Because of this low degree of scatter and because of the fact that this climate contains many data points, no coefficients are given in this section.

2.4.2. Humid, T_{max}-T_{min}: 15-20 °C

This class contains rather few cases. The individual relationship between minimum temperature and actual vapour pressure is given in equation (23). Explanation of the parameters is the same as for equation (22).

$$e_d = 0.892 * \exp(0.056 * T_{min}) \qquad (23)$$

Common features of the stations belonging to this class are given in Table 2.4.

Table 2.4. Parameter ranges of the H1520 climate.

	T_{max}	T_{min}	RH	R_s	n/N
	°C	°C	%	$Mj/m^2.d$	%
Min. Value	17	2	50	13	20
Max. Value	37	20	95	24	80

A scrutiny of the data belonging to this class, revealed that this class only contains African and South-American stations.
The following table (Table 2.5) gives some coefficients, by which 0.892 and C_f have to be replaced in equation (23) and (14), respectively.

Table 2.5. Individual (in stead of 0.892) and overall coefficients in the T_{min}-e_d relationship for the H1520 climate.

Country	Height	Site	Coefficient	
			individual	overall (C_f)
Sudan	all		0.93	0.76
Ethiopia	For this country no consistent relationship between coefficient and certain properties related to the situation of the station was found			
Uganda	all		0.94	0.81
Liberia	all		0.75	0.61
Angola	all		1.00	0.83
Mozambique	all		0.88	0.72
Mexico	all		0.98	0.80
Haiti	all		0.97	0.79
Honduras		Coast	1.12	0.92
		Interior	1.00	0.85
Venezuela	all		1.12	0.90
Brasil	0–450		1.04	0.85
	>450		0.89	0.75
Peru	>3000		0.66	0.65
Paraguay	126		1.01	0.87
Argentina	81		0.74	0.61

Sometimes it is very difficult to find general coefficients for a country. Ethiopia, for example, is such a country. Because no descriptions of the areas (swamp, irrigated area, dry zone) are available and fixing of a station by means of the atlas is difficult, it is hard to relate the coefficients to a certain area. To illustrate this, Table 2.6 gives the coefficients for Ethiopia.

Table 2.6. Overall and individual coefficients for the Ethiopian stations belonging to the H1520-class.

Station	Country	Lat.	Long.	Height	Mo	Tmin	VP	Cf1	Cf2
63.02900	ETH	14.53	38.49	2022	7	5.70	1.39	.93	1.01
63.02900	ETH	14.53	38.49	2022	8	6.60	1.40	.88	.97
63.31400	ETH	12.57	36.04	803	6	19.90	2.54	.67	.83
63.31700	ETH	12.20	37.14	2150	7	8.40	1.51	.84	.94
63.31700	ETH	12.20	37.14	2150	8	8.70	1.52	.83	.93
63.32000	ETH	11.53	38.02	2410	6	9.00	1.39	.74	.84
63.32300	ETH	11.17	36.55	2180	6	9.50	1.42	.73	.83
63.32400	ETH	11.13	40.03	1660	7	10.70	1.46	.69	.80
63.32400	ETH	11.13	40.03	1660	8	9.70	1.41	.72	.82
63.33500	ETH	12.31	39.41	2200	3	13.50	1.41	.56	.66
63.33500	ETH	12.31	39.41	2200	7	15.60	2.13	.73	.89
63.33800	ETH	10.54	39.50	1600	8	13.90	1.69	.65	.78
63.34600	ETH	10.01	39.59	1300	7	16.80	1.62	.52	.63
63.35100	ETH	9.32	37.23	2320	6	8.50	1.25	.69	.78
63.35900	ETH	9.00	36.06	1200	10	13.00	1.58	.64	.76
63.36000	ETH	8.58	34.35	2040	5	12.10	1.88	.81	.95
63.43500	ETH	8.10	34.15	550	7	16.90	2.26	.72	.88
63.43700	ETH	8.08	39.35	2600	7	7.50	1.52	.90	1.00
63.43700	ETH	8.08	39.35	2600	8	8.10	1.54	.87	.98
63.44300	ETH	7.51	36.38	1560	5	13.70	1.89	.74	.88
63.44500	ETH	7.48	34.24	530	7	16.00	2.37	.80	.97
63.44500	ETH	7.48	34.24	530	8	16.20	2.43	.81	.98
63.44500	ETH	7.48	34.24	530	10	16.20	2.05	.68	.83
63.45700	ETH	7.16	36.11	1950	4	11.50	1.62	.73	.85
63.45700	ETH	7.16	36.11	1950	5	11.50	1.70	.77	.89
63.46100	ETH	7.05	35.15	1200	5	13.50	1.95	.77	.92
63.46100	ETH	7.05	35.15	1200	7	13.40	2.14	.85	1.01
63.48000	ETH	7.13	36.17	1725	4	12.70	1.73	.72	.85
63.48100	ETH	6.58	39.11	2540	7	5.10	1.18	.82	.89
63.48100	ETH	6.58	39.11	2540	8	5.10	1.24	.86	.93
63.48800	ETH	6.45	38.23	1835	4	11.10	1.67	.77	.90
63.49800	ETH	6.35	38.25	1860	4	10.20	1.61	.79	.91
63.49800	ETH	6.35	38.25	1860	5	8.90	1.60	.86	.97
63.49800	ETH	6.35	38.25	1860	8	9.10	1.54	.81	.93
63.49800	ETH	6.35	38.25	1860	9	9.40	1.59	.82	.94
63.49800	ETH	6.35	38.25	1860	10	8.30	1.38	.77	.87
63.50500	ETH	6.25	38.18	1670	4	13.50	1.88	.74	.88

2.4.3. Humid, T_{max}-T_{min}: 20-40 °C.

Only three (!) stations could be detected with a month yielding more than 150 mm of rain , having a temperature difference of more than 20 °C at the same time.
These stations were related to high maximum temperatures (> 35 °C). Because a relationship based on three points is not really justified and the probability of any irrigation site falling in this class is very small, no individual relationship is provided here.
Salient features are given below.

Table 2.7. Parameter ranges of the H2040 climate.

	T_{max}	T_{min}	RH	R_s	n/N
	°C	°C	%	$Mj/m^2.d$	%
Min. Value	35.4	14.8	48	16	36
Max. Value	37.4	17.3	62	19	53

This class comprised 2 stations in Ethiopia (1300 and 530 m height, and 1 station at Liberia (height: 300 m)

2.4.4. Subhumid, T_{max}-T_{min}: < 15 °C

This class contained many cases. It was therefore not possible to enumerate all coefficients. For this reason, only the data of Europe were analyzed. As one can see in Table 2.9, overall coefficients are varying already considerably.
It appeared that most of the times coastal regions and islands had a lower coefficient. This is probably caused by the fact that minimum temperatures are fairly higher for those places compared to stations sited in the interiors of a country.
No general coefficients for Europe could be given. The coastal regions in Portugal and Greece appear to have higher coefficients than the ones of Yugoslavia, Italy and Spain, for example. Still, the variation is rather small and generalization (by averaging) of, for example, the Mediterranean countries seems possible.

The individual relationship between T_{min} and e_d is as follows.

$$e_d = 0.624 * \exp (0.0632*T_{min}) \qquad (24)$$

Possible parameter ranges for this climate are listed in Table 2.8.

Table 2.8. Parameter ranges of the SH15 climate.

	T_{max}	T_{min}	RH	R_s	n/N
	°C	°C	%	$Mj/m^2.d$	%
Min. Value	-5	-14	48	2	10
Max. Value	42	31	62	26	80

Table 2.9. Overall coefficients for European stations of the SH15-climate.

Country	Specifics	Coefficient C_f
Belgium	Height > 500	0.68
	Coastal area, Plains	0.65
Luxembourg		0.76
France	Coast Channel	0.60
	Coast Mediterranean	0.57
	River area	0.57
	Les Landes/Gascogne	0.70
	Massif Central	0.62
	Dauphine	0.67
	Corsica	0.65
	Others	0.65
Spain	Coastal town North	0.58
	Coastal region North	0.61
	Coastal town West	0.53
	Coastal region West	0.59
	Coastal town East	0.54
	Gulf of Valencia,	
	Mallorca	0.60
	Menorca	0.56
	Ibiza	0.48
	Interior	0.62
Portugal	Coastal area West	0.73
	Interior > 500 m	0.77
Capeverdian Islands		0.54
Yugoslavia	Coastal town	0.49
	Coastal area	0.56
	Coastal area > 500	0.69
	River area	0.53
	Interior	0.64

Italy	Coastal town	0.52
	Gulf of Genua	0.56
	Coastal area	0.60
	Interior	0.61
	Karmish Alps	0.66
	Sardinia	0.65
Greece	Northern Coast	0.63
	Southern Coast	0.62
	Western Coast	0.59
	Eastern Coast	0.60
	Interior	0.61
	Islands	0.53

2.4.5. Subhumid, T_{max}-T_{min}: 15-20 °C

Actual vapour pressure as a function of minimum temperature can be described by the following relationship.

$$e_d = 0.805 * \exp(0.051 * T_{min}) \qquad (25)$$

Ranges of relevant parameters are given in Table 2.10.

Table 2.10. Parameter ranges of the SH1520 climate.

	T_{max}	T_{min}	RH	R_s	n/N
	°C	°C	%	Mj/m².d	%
Min. Value	12	-5	30	10	30
Max. Value	38	25	100	26	90

Besides stations in Africa and South-America this division led to some Asian stations (Turkey (2), Afghanistan (1), Sri Lanka (1), Burma(1), Thailand(1), China(10))
The stations in Turkey, Afghanistan, Sri Lanka and Burma were sited in mountainous areas.
Because the coefficients are of a very capricious nature for certain countries, not all coefficients are included in Table 2.11.

Table 2.11. Coefficients for several countries of the SH1520-climate.

Country	Height	Extra	Coefficient individual	Coefficient overall (C_f)
Turkey	2000		0.82	0.75
Afghanistan	1200		0.79	0.67
Sri Lanka	1880	Island	1.02	0.85
Burma	1078		0.61	0.46
Thailand	395		0.84	0.61
Sudan		month 0-6	0.68	0.49
		month 7-12	0.89	0.67
Uganda		month 0-6	0.73	0.54
		month 7-12	0.88	0.67
		near lake	1.04	0.84
Zaire			0.88	0.70
Burundi			0.80	0.66
Centrafrica			0.70	0.50
Liberia			0.80	0.60
Angola		Coastal area	1.16	0.88
	>1000	rain>100	0.95	0.73
	>1000	rain<100	0.52	0.40
Mozambique		Coast	0.97	0.73
		Interior	0.84	0.62
Zambia			0.67	0.52
Namibie			0.57	0.43
South-Africa		River area	0.63	0.50
		Interior	0.74	0.60
Mexico		s.coast	1.07	0.81
	>2000		0.82	0.69
		e.coast	0.72	0.54
Haiti			1.00	0.76
Guatemala	>1000		0.88	0.67
Honduras	<100	n.coast	1.18	0.94
Ecuador	>2500		0.77	0.67
Chili	<1000		0.77	0.75
Paraguay		month 1-6	0.99	0.83
		month 7-12	0.85	0.64
Uruguay			0.76	0.58
Sumatra	>500		0.90	0.69
Borneo			0.96	0.71

2.4.6. Subhumid, $T_{max}-T_{min}$: 20–40 °C.

Eq. (26) gives the individual relationship between minimum temperature and actual vapour pressure for the SH2040-climate.

$$e_d = 1.07 * \exp (0.040*T_{min}) \qquad (26)$$

Table 2.12 gives the maximum variation of several parameters needed for Eq. (1).

Table 2.12. Parameter ranges of the SH2040 climate.

	T_{max}	T_{min}	RH	R_s	n/N
	°C	°C	%	Mj/m².d	%
Min. Value	19	-3	50	11	44
Max. Value	41	18	100	24	83

2.4.7. Semi-arid, $T_{max}-T_{min}$: < 15 °C.

The dependence of actual vapour pressure on minimum temperature was given by;

$$e_d = 0.612 * \exp (0.059*T_{min}) \qquad (27)$$

This climate can be described by the following characteristic parameter values.

Table 2.13. Parameter ranges of the SA15 climate.

	T_{max}	T_{min}	RH	R_s	n/N
	°C	°C	%	Mj/m².d	%
Min. Value	-8	-18	22	2	10
Max. Value	42	30	100	27	95

Because of the large amount of stations comprising in this class no table of coefficients is supplied.

2.4.8. Semi-arid, $T_{max}-T_{min}$: 15-20 °C

The relationship between actual vapour pressure and minimum temperature was given by;

$$e_d = 0.682 * \exp(0.054*T_{min}) \tag{28}$$

In table 2.14 the maximum and minimum possible parameter values are given.

Table 2.14. Parameter ranges of the SA1520 climate

	T_{max}	T_{min}	RH	R_s	n/N
	°C	°C	%	$Mj/m^2.d$	%
Min. Value	-8	-22	20	5	30
Max. Value	42	28	80	30	95

2.4.9. Semi-arid, $T_{max}-T_{min}$: 20-40 °C

The relationship between actual vapour pressure and minimum temperature was given by;

$$e_d = 0.734 * \exp(0.065*T_{min}) \tag{29}$$

This climate can be described by the following characteristic parameter values.

Table 2.15. Parameter ranges of the SA2040 climate.

	T_{max}	T_{min}	RH	R_s	n/N
	°C	°C	%	$Mj/m^2.d$	%
Min. Value	-11	-8	38	13	38
Max. Value	42	18	88	27	98

2.4.10. Arid, T_{max}–T_{min} : < 15°C

Formula 30 gives actual vapour pressure as a function of minimum temperature

$$e_d = 0.521 * \exp (0.062*T_{min}) \tag{30}$$

Possible ranges of maximum and minimum temperature, relative humdity, incoming global radiation, and relative sunshine fraction are listed in Table 2.16

Table 2.16. Parameter ranges of the A15 climate.

	T_{max}	T_{min}	RH	R_s	n/N
	°C	°C	%	Mj/m².d	%
Min. Value	−20	−35	20	2	20
Max. Value	43	32	95	30	95

2.4.11. Arid, T_{max}–T_{min} : 15–20 °C

Formula 31 gives the relationship between actual vapour pressure and minimum temperature.

$$e_d = 0.621 * \exp (0.041*T_{min}) \tag{31}$$

Possible ranges of maximum and minimum temperature, relative humdity, incoming global radiation, and relative sunshine fraction are listed in Table 2.17

Table 2.17. Parameter ranges of the A1520 climate.

	T_{max}	T_{min}	RH	R_s	n/N
	°C	°C	%	Mj/m².d	%
Min. Value	−25	−39	10	3	50
Max. Value	45	30	80	32	95

2.4.12. Arid, $T_{max}-T_{min}$: 20-40 °C

Actual vapour pressure as a function of minimum temperature is shown in Eq. (32).

$$e_d = 0.588 * \exp(0.046*T_{min}) \quad (32)$$

Upper and lower limits of relevant variables are given in Table 2.18.

Table 2.18. Parameter ranges of the A2040 climate

	T_{max}	T_{min}	RH	R_s	n/N
	°C	°C	%	$Mj/m^2.d$	%
Min. Value	-5	-20	20	4	40
Max. Value	45	40	75	32	95

2.5. Standardization of the Radiation Term of Equation (1).

Standardization of the radiation term (as part of the development of a reviewed Temperature Method based on Eq. (1)), was done in a way similar to the one described in Section 1.1 of Doorenbos and Pruitt (1977). The same three classes of relative sunshine fraction, n/N, were adopted;

n/N low	:	± 45 %
n/N medium	:	± 70 %
n/N high	:	± 90 %

The division of relative sunshine fraction into 3 classes, resulted in the fact that no direct global radiation measurements were necessary.
Hence, the methods which have this standardization incorporated and therefore only need estimates of relative sunshine fraction (and thus of global radiation) are denoted as Temperature Method. This yielded the so-called extended Temperature and the Standardized Temperature Method. The first one mentioned requires measured values of actual vapour pressure and windspeed, the latter one uses estimates of these entities by asking the user for estimates of average daily relative humidity.
In real life it would be unrealistic to have the disposal of detailed humidity measurements and not of simple sunshine duration recordings. For this reason, the extended Temperature Method is used only as comparative material.

The results of Chapter 3 might indicate that three classes are insufficient to describe relative sunshine fraction properly.

2.6. Simplification of the Radiation Term of Equation (1).

In their attempt to calculate potential evapotranspiration many users are hampered by the fact that they have only the disposal of very limited climatic data. In these situations a simple temperature method will be indispensable. The FAO Temperature Method, described in Irrigation and Drainage Paper No. 24, is based on the original Blaney-Criddle method. It uses measured temperature data as well as estimated levels of humidity, sunshine and wind.
In order to get rid of the sometimes unreliable estimated values, it was proposed by the experts convening in the FAO consultation of May 1990 to improve global radiation estimates for the radiation term by a relationship between relative sunshine fraction and $T_{max}-T_{min}$.

In Chapter 1 however, it was found that the correlation between $T_{max}-T_{min}$ and n/N is very low (see for example Fig. 2.5). Furthermore it seems more straightforward to relate a temperature based parameter directly to global incoming radiation in stead of relating it to sunshine duration which has to be recalculated to incoming radiation by using the rather crude Angström values.

It appeared that for all climatic classes as given above, a relationship could be detected between maximum temperature and incoming global radiation. This relationship is based on the fact that the part of the global radiation not used for evapotranspiration will be transformed into a temperature increase of the earth's surface. The same kind of relationship exists between average temperature and incoming global radiation. Still, it was decided to take Tmax as the independent variable as this requires one computation less (if we assume $T_{avg} = (T_{max} + T_{min})/2$).
Fig. 2.13 shows that the correlation is promising, but that at a certain maximum temperature, incoming global radiation still could vary considerably.

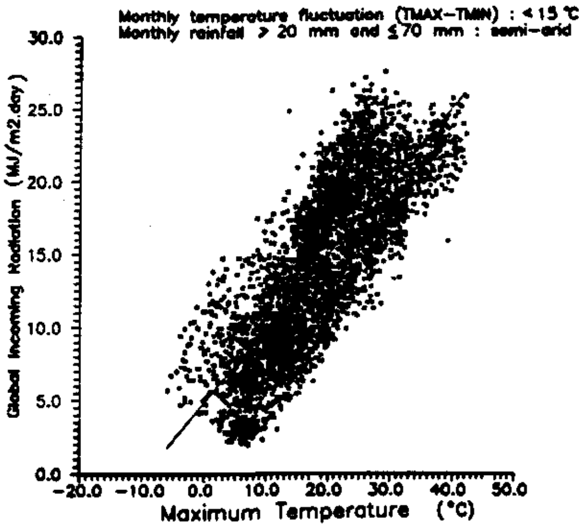


Fig. 2.13. Incoming global radiation (R_s) as determined by maximum air temperature (T_{max}) for a semi-arid climate.

A relationship between relative sunshine fraction and maximum temperature also exists, but it appears to be more scattered.
(See Fig. 2.14).

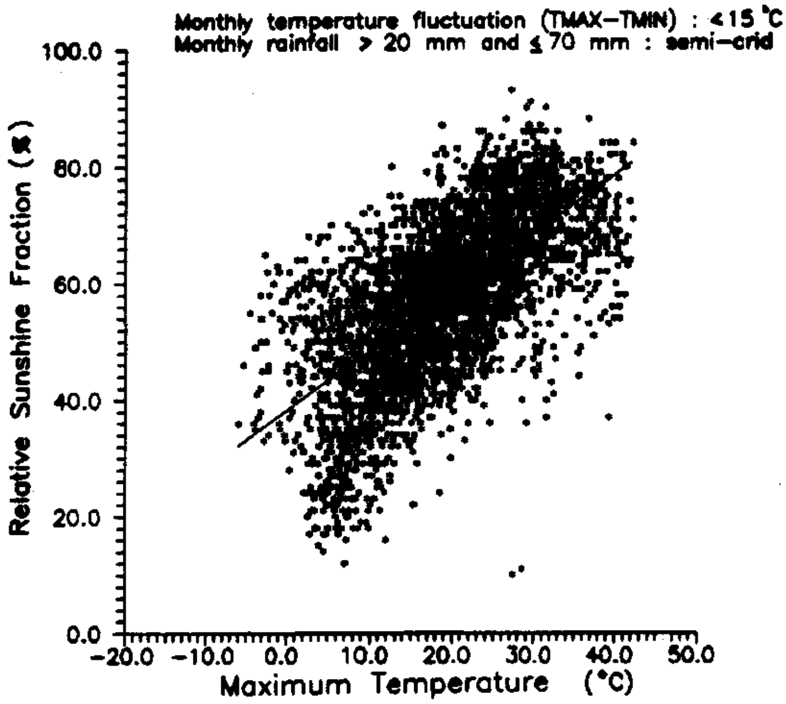


Fig. 2.14. Relative sunshine fraction (n/N) as a function of maximimum air temperature (T_{max}) for the SA15-climate.

Therefore an extra parameter had to be searched for which could enable the user to find a reasonable estimation of incoming solar radiation out of (maximum) temperature measurements only.

At first it was assumed that this auxiliary variable might be found in the variation of maximum temperature during the season.
This assumption was based on the fact that the incoming global radiation measured at a certain meteorlogical station shows a 'looping' effect.
This phenomenon can be seen in Fig. 2.15. It is clear that global radiation depends differently on maximum temperature, depending on the season in which the data are measured.
The upper part can be described mathematically by a second order polynomial, the lower part by an exponential function.
The shape of the ellips is determined by the variation in maximum temperature. A meteorological station at the coast for example will result in a shorter long axis than a station sited in a mountanous area.

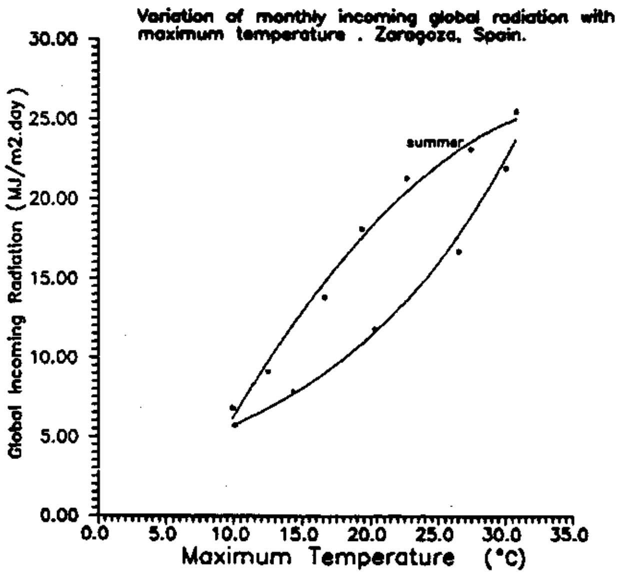


Fig. 2.15. Seasonal variation of incoming global radiation (R_s) with maximum temperature (T_{max}) for one single station in Zaragoza, Spain.

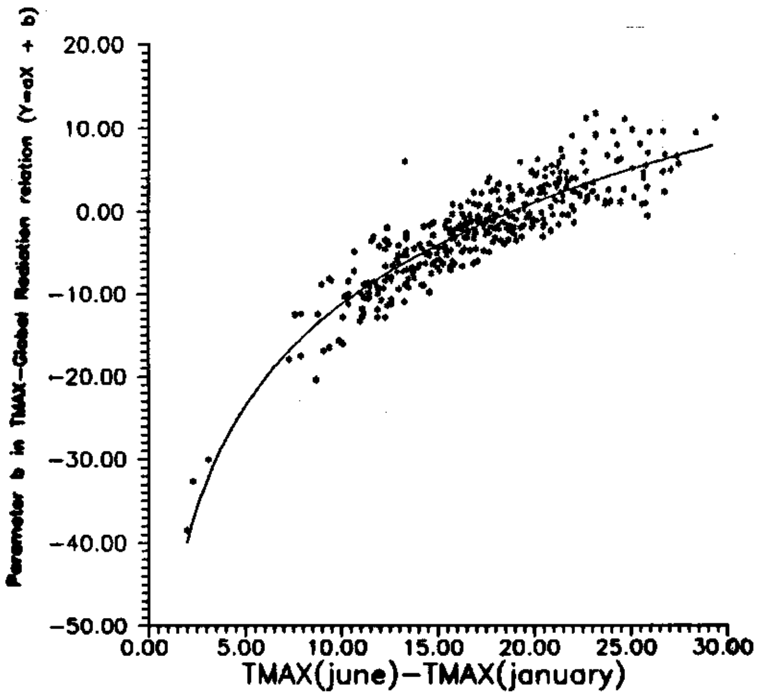
Based on this concept, the relation between maximum temperature and incoming global radiation per station were to be described by two linear equations. One for the 'summer' season (january-june), and one for the 'winter' season, as a cause of the 'looping-effect'.
They were characterized by a simple linear-type relationship, namely:

$$R_s(i,j) = a(i) * T_{max}(i,j) + b(i) \tag{33}$$

R_s = Global radiation in month j of season i $[MJ/m^2.d]$
T_{max} = Maximum temperature in month j of season i [°C]
a = Parameter a for season i $[MJ/m^2.d.°C]$
b = Parameter b for season i $[MJ/m^2.d]$
i = 1 for the 'summer' and 2 for the 'winter' season respectively.
j = 1,2,3,4,5 or 6. 1 referring to january and july, 2 to february and august, 3 to march and september, 4 to april and october, 5 to may and november and 6 to june and december.

For determination of the parameters a and b the auxiliary variables T_{max}(june)$-T_{max}$(january) and T_{max}(december)$-T_{max}$(july) were used. From now on they will be referred to as δTMAX1 and δTMAX2.
It appeared that both a and b revealed an exponential dependence on δTMAX.
A graphical representation of this statement is given in Fig. 2.16, which shows the a and b factors as a function of δTMAX1 for several sites in Europe.
The shapes of the curves can be described by the functions;

$$a = -0.811 * \ln(\delta TMAX1) + 3.29 \tag{34}$$
$$b = 17.79 * \ln(\delta TMAX1) - 52.26 \tag{35}$$



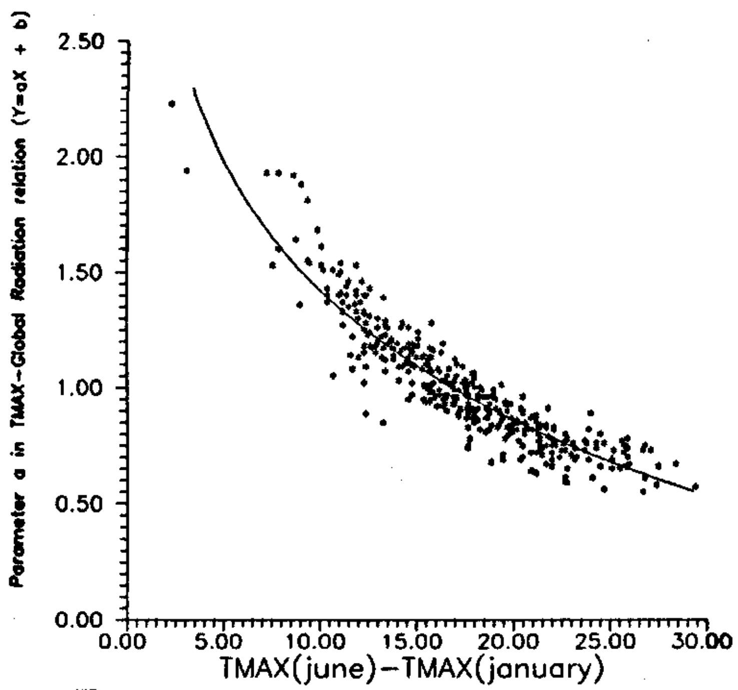


Fig. 2.16 Parameters a and b in the relationship $R_s = a*T_{max}+b$ as a function of δTMAX1. Only European stations were considered.

It appeared however that this concept was not working satisfactorily in the case of, for example, many humid tropical countries. In these cases δTMAX can be very small or even negative and this may yield unrealistic a and b-values.

Alternative relationships

Other attempts to find a proper relationship between a certain 'easy available parameter' and relative sunshine fraction or global radiation resulted to be less promising than the maximum temperature option. The relationship between for example monthly rainfall amount or station height and relative sunshine fraction are given in Figs. 2.17 and 2.18.
Although certain trends can be observed, the correlations are much too poor to base reliable predictions on.

Besides maximum temperature, another parameter which logically has to be be connected with relative sunshine fraction or incoming radiation is relative humidity (or any other parameter related to relative humidity, like vapour pressure or vapour pressure deficit.)

Example of the performance of these variables as predictors of relative sunshine fraction and incoming radiation are given in the Figs. 2.19 and 2.20.

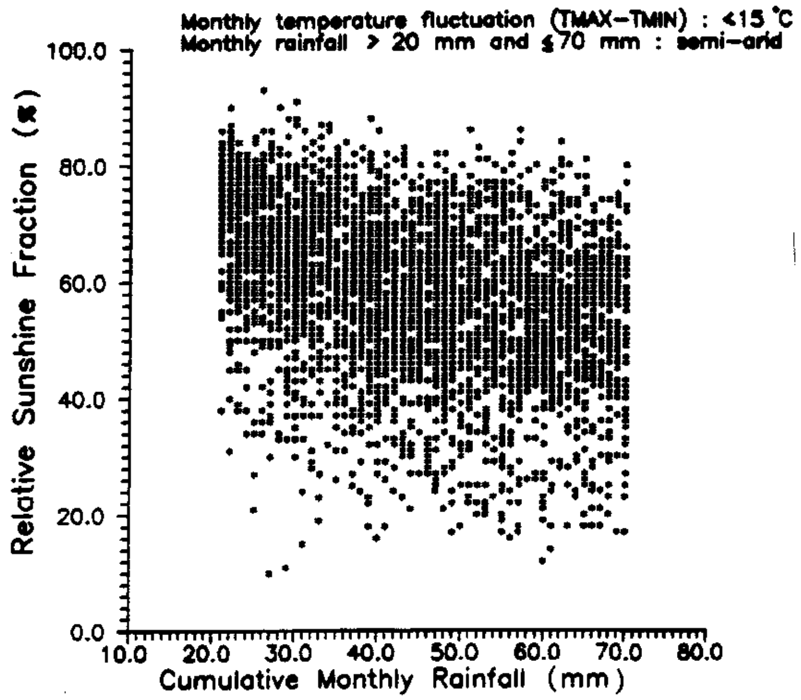


Fig. 2.17. The relationship between relative sunshine fraction (n/N) and cumulative monthly rainfall amount for stations of the SA15-climate.

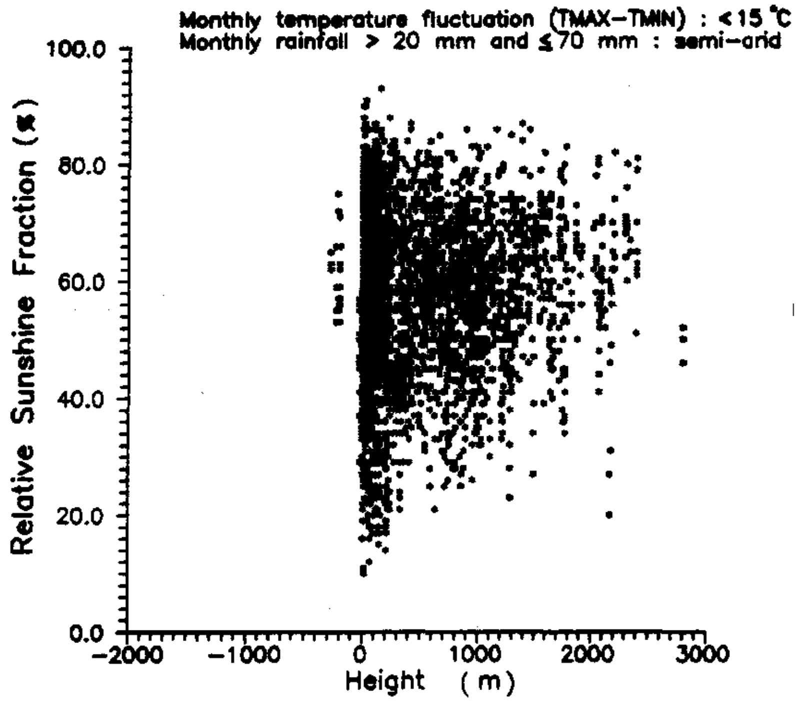


Fig. 2.18. The relationship between relative sunshine fraction (n/N) and station height for stations of the SA15-climate.

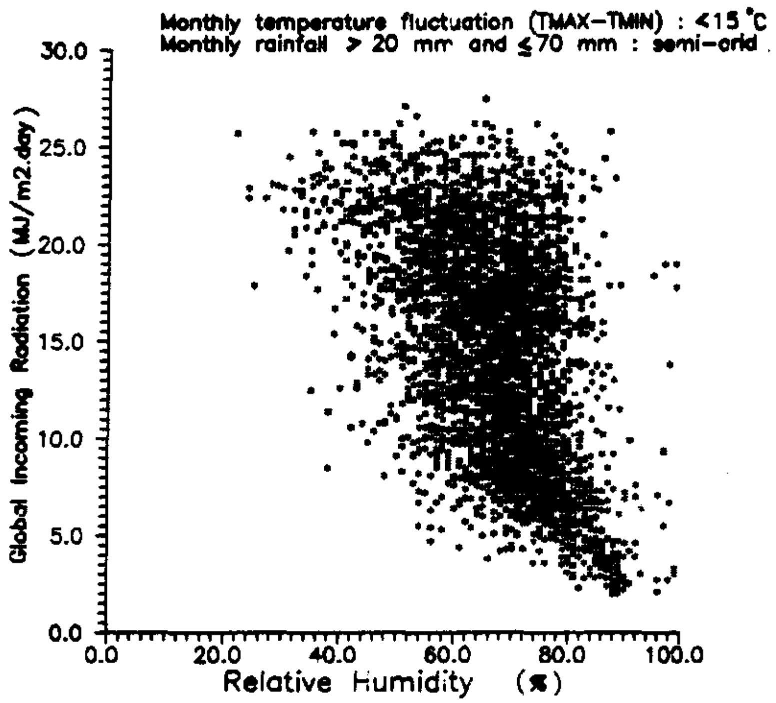
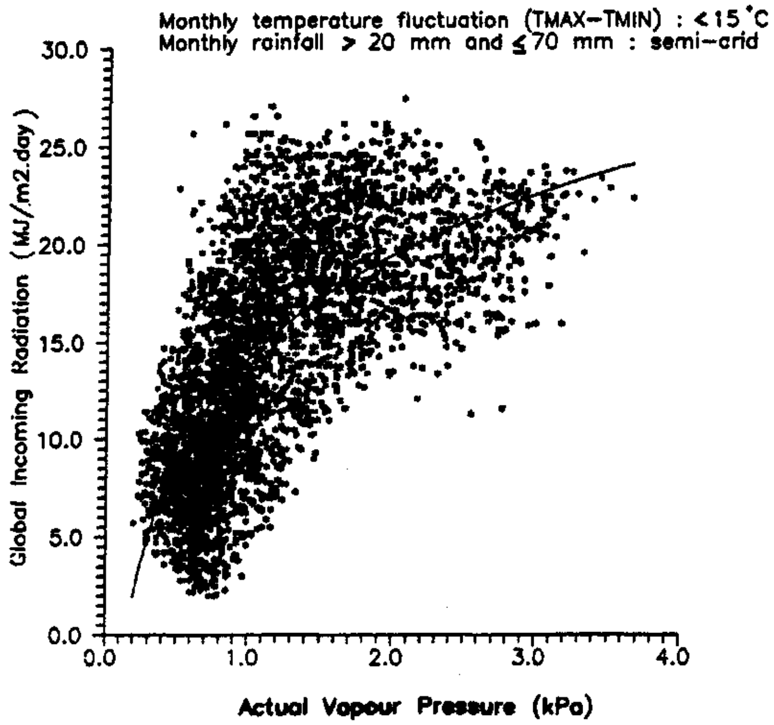


Fig. 2.19. Global incoming radiation (R_s) as a function of relative humidity (RH) for stations of the SA15-climate.

The relationship between relative humidity and relative sunshine fraction seems good enough to use as a substitue if no measured sunshine data are available.
It has to be recalled however that one of the disadvantages of a real Temperature method lies in the non-availability of directly measured humidity data. Therefore, relative humidity or vapour pressure deficit have to be derived first from the empirical relationship between minimum temperature and actual vapour pressure.
This might lead to extra uncertainties in the value of n/N or global radiation.
For this reason it was decided to compare the predictive potential of both relationships based on temperature and on relative humidity.
In the comparative model PEVAP.FOR (See Appendix 1), relationships between maximum temperature and global incoming radiation, between maximum temperature and relative sunshine fraction and between relative humidity and relative sunshine fraction were entered.



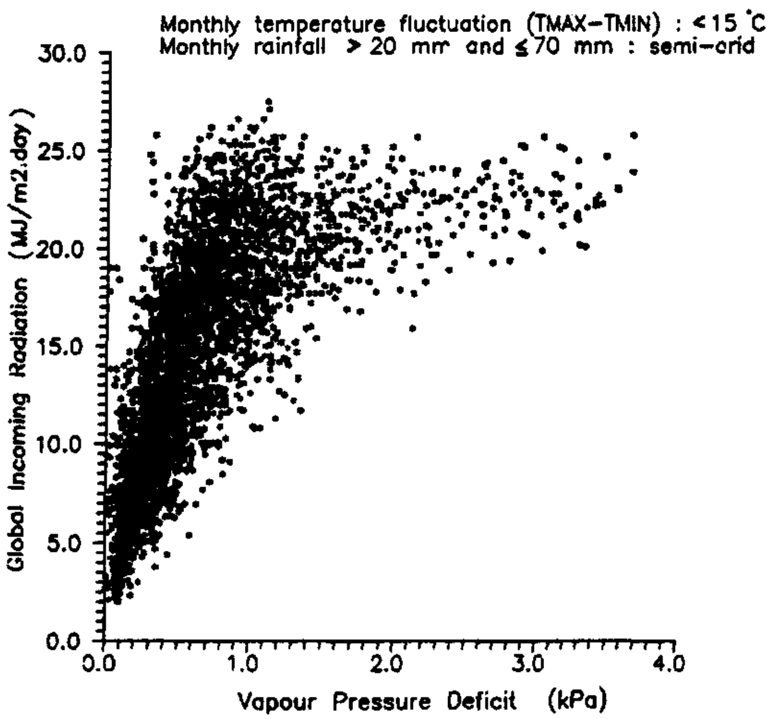


Fig. 2.20. Global incoming radiation (R_s) as a function of vapour pressure (e_d) and vapour pressure deficit (e_a−e_d) for stations of the SA15-climate.

3. Comparison of Reviewed Methods with other selected methods.

3.1. Results of Comparison.

For comparison of the reviewed FAO Radiation method and formerly developed radiation methods 4 arbitrary Climate Classes were chosen to describe the humid, subhumid, semi-arid and arid climates. They were the H15, the SH15, the SA1520 and the A2040 respectively.

In order to allow uniform comparison of the various equations, varying from extended to simplified methods, the Extended Radiation method was taken as a reference. This is formula 1 with only **measured** parameter-values as input.
It would have been better to take **directly measured** evapotranspiration data as standard, but these data were not available for the weather stations gathered in the FAO-datafiles.
Reliable measurements of (potential) evapotranspiration can be obtained by lysimeter experiments. Because the equipment for lysimeter experiments is very costly and requires a lot of maintainance, very few meteorological stations are actually provided with this method.

For the computer-aided comparison of the methods explained in Section 1.1 and 1.2, the program PEVAP.FOR was written. It is given in Appendix 1. The program will ask the user to enter the main Climate Class (humid, subhumid, semi-arid and arid), the Temperature Difference Class (<15 °C, 15-20 °C, and > 20 °C), and the method by which global incoming radiation has to be calculated.
The several classes can be described by the numbers given in the table below.

Table 3.1. Interactive input to the program PEVAP.FOR

Climate Class		Temperature difference Class	
Humid	1	< 15 °C	1
Subhumid	2	15-20 °C	2
Semi-arid	3	20-40 °C	3
Arid	4		

The stations of the twelve possible climates resulting from this division were characterized by stationnumber, latitude, longitude, height, month, rainfall, average temperature, maximum temperature, minimum temperature, temperature difference ($T_{max}-T_{min}$), relative sunshine fraction, incoming global radiation, vapour pressure, vapour pressure deficit, relative humidity and wind speed.

These values were provided in twelve separate files by the programs READLT15.FOR, READ15-20.FOR, and READ20-40.FOR. (See Appendix 4).

Table 3.2 gives the status of these variables in the various Radiation and Temperature Methods used in the Comparison. The meaning of the applied abbreviations is as follows.

RADEXT - Extended Radiation Method (Formula 1)
RADSTA = Standardized Radiation Method
RADSIM - Simplified Radiation Method
RADORI - Original FAO Radiation Method
RADPRI - Priestley-Taylor Method
TEMEXT = Extended Temperature Method
TEMSTA = Standardized Temperature Method
TEMSIM - Simplified Temperature Method
TEMHAR - Hargreaves Method

Table 3.2. Status of relevant variables in methods used for calculation of potential evapotranspiration

	RADEXT	RADSTA	RADSIM	RADORI	RADPRI	TEMEXT	TEMSTA	TEMSIM	TEMHAR
Latitude						*	*	*	*
Longitude									
Height	*	*	*	*	*	*	*	*	
Month						*	*	*	*
T_{max}	*	*	*	*	*	*	*	*	*
T_{min}	*	*	*	*	*	*	*	*	*
$T_{max}-T_{min}$									*
n/N	*	*	*		*	E	E		
R_s	*	*	*	*	*			$f(T_{max})$	
R_a						*	*	*	*
e_d	*		$f(T_{min})$			*		$f(T_{min})$	
e_a-e_d	*					*			
RH		E		E			E		
U_2	*	E	E	E		*	E	E	
C_f			*					*	

* Direct value used (measured parameter or predefined coefficient)
E Estimated value used

In order to arrive at the simplified (Radiation and Temperature) versions of Eq.(1), several empirical relationships between easily available variables on the one side and moisture (vapour pressure) and radiation (incoming global radiation/relative sunshine fraction) parameters at the other hand were possible.
The options are listed below in Table 3.3.

Table 3.3 Empirical equations and accessory coefficients derived for the Simplified Methods

Climate	Equation	Coefficient
Vapour pressure = $f(T_{min})$ [kPa]		
Humid	$e_d = C_f * \exp \frac{(T_{min} * 17.27)}{(T_{min} + 237.3)}$	$C_f = 0.61$
Subhumid	" "	$C_f = 0.61$
Semi-arid	" "	$C_f = 0.55$
Arid	" "	$C_f = -0.016 * T_{min} + 0.66$
Vapour pressure = $f(e_a(T) - \gamma(T_{max} - T_{min}))$		

For example $e_d = 0.75*(e_a(T_{min}) - \gamma(T_{max}-T_{min})) + 8.36$

(Smith, personal communication)

Incoming Global Radiation = $f(T_{max})$ [MJ/m^2.d] Method 1		
Humid		
	$\delta T < 15$ °C	$R_s = 0.45 * T_{max} + 3.3$
	$\delta T = 15-20$ °C	$R_s = 0.13 * T_{max} + 14.4$
	$\delta T = 20-40$ °C	$R_s = 1.56 * T_{max} - 39.4$
Subhumid	$\delta T < 15$ °C	$R_s = 0.62 * T_{max} + 0.7$
	$\delta T = 15-20$ °C	$R_s = 0.16 * T_{max} + 15.6$
	$\delta T = 20-40$ °C	$R_s = 0.17 * T_{max} + 13.9$
Semi-arid	$\delta T < 15$ °C	$R_s = 0.66 * T_{max} + 2.4$
	$\delta T = 15-20$ °C	$R_s = 0.31 * T_{max} + 11.1$
	$\delta T = 20-40$ °C	$R_s = 0.31 * T_{max} + 11.1$
Arid	$\delta T < 15$ °C	$R_s = 0.41 * T_{max} + 8.3$
	$\delta T = 15-20$ °C	$R_s = 0.37 * T_{max} + 8.9$
	$\delta T = 20-40$ °C	$R_s = 0.28 * T_{max} + 11.6$

$n/N = R_s/(b*R_a) - a/b$

Where R_a is extraterrestial radiation and a and b are climate-dependent Angström variables. See Section 1.5
n/N is limited by the values 0.10 and 0.95

Relative Sunshine Fraction			*= f*(T_{max})	Method 2
Humid				
	δT	< 15 °C	$n/N = 0.42 * T_{max} + 32.4$	
	δT	= 15–20 °C	$n/N = 0.25 * T_{max} + 40.7$	
	δT	= 20–40 °C	$n/N = 9.40 * T_{max} -298.6$	
Subhumid	δT	< 15 °C	$n/N = 1.09 * T_{max} + 28.5$	
	δT	= 15–20 °C	$n/N = 0.57 * T_{max} + 43.1$	
	δT	= 20–40 °C	$n/N = 0.20 * T_{max} + 51.4$	
Semi-arid	δT	< 15 °C	$n/N = 1.37 * T_{max} + 30.6$	
	δT	= 15–20 °C	$n/N = 0.40 * T_{max} + 56.4$	
	δT	= 20–40 °C	$n/N = 0.01 * T_{max} + 67.3$	
Arid	δT	< 15 °C	$n/N = 0.50 * T_{max} + 61.7$	
	δT	= 15–20 °C	$n/N = 0.30 * T_{max} + 70.6$	
	δT	= 20–40 °C	$n/N = 0.35 * T_{max} + 70.3$	

$R_s = (a + b(0.01*n/N))*R_a$

Incoming Global Radiation = f(RH)	[MJ/m²·d]	Method 3
Humid	$R_s = -0.18 * RH + 27.0$	
Subhumid	$R_s = -0.15 * RH + 29.3$	
Semi-arid	$R_s = -0.13 * RH + 27.0$	
Arid	$R_s = -0.12 * RH + 25.6$	

$n/N = f(T_{max})$

Estimates of potential evapotranspiration by the standardized, simplified and other selected equations versus the outcomes of the Extended Radiation Method (Eq. (1)) are graphically depicted in Figs. 3.1–3–7.

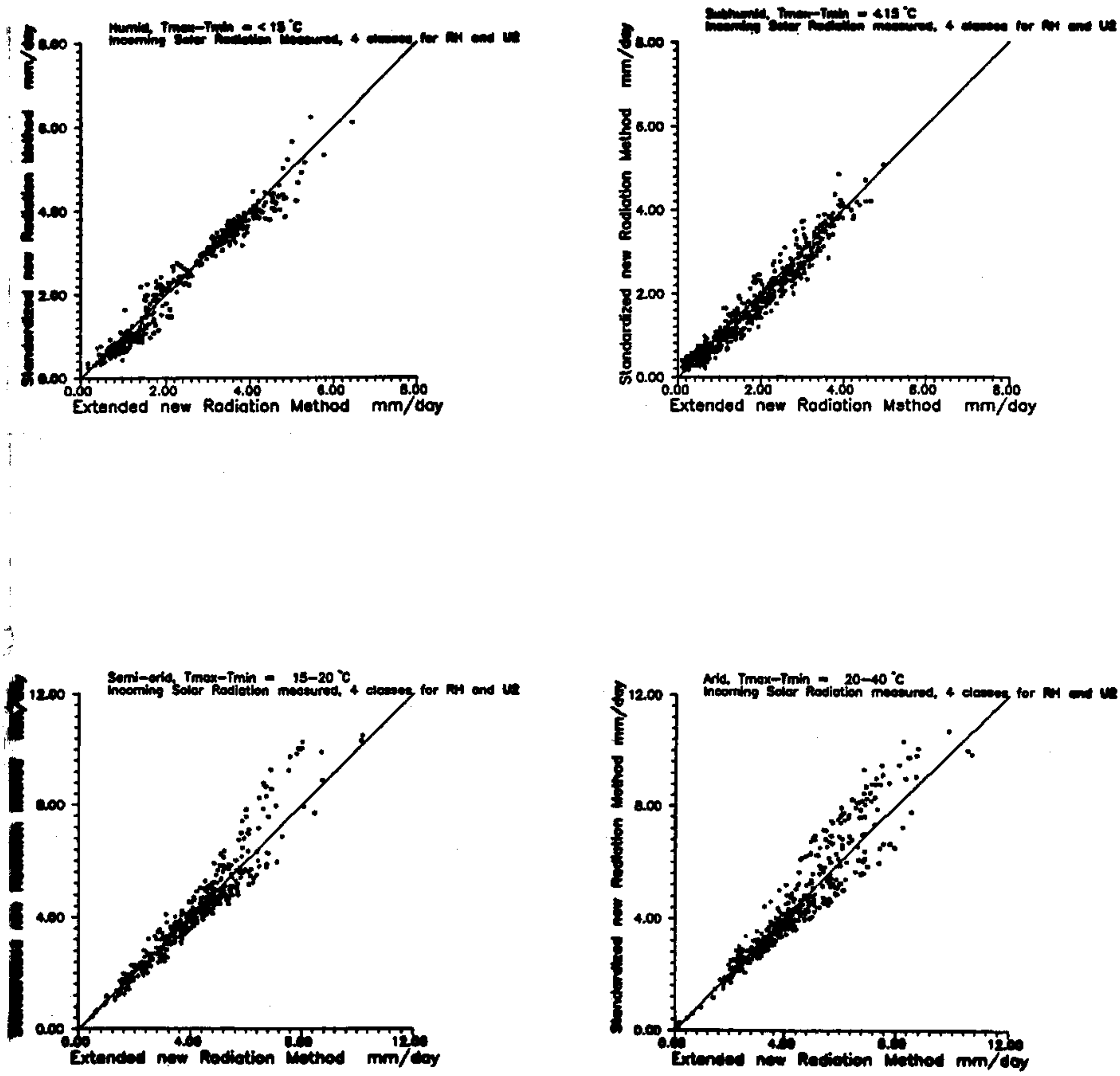


Fig. 3.1. Monthly potential evapotranspiration according to the Standardized new Radiation method versus the Extended new Radiation method for all four climate types. In all figures the 45°-line is given.

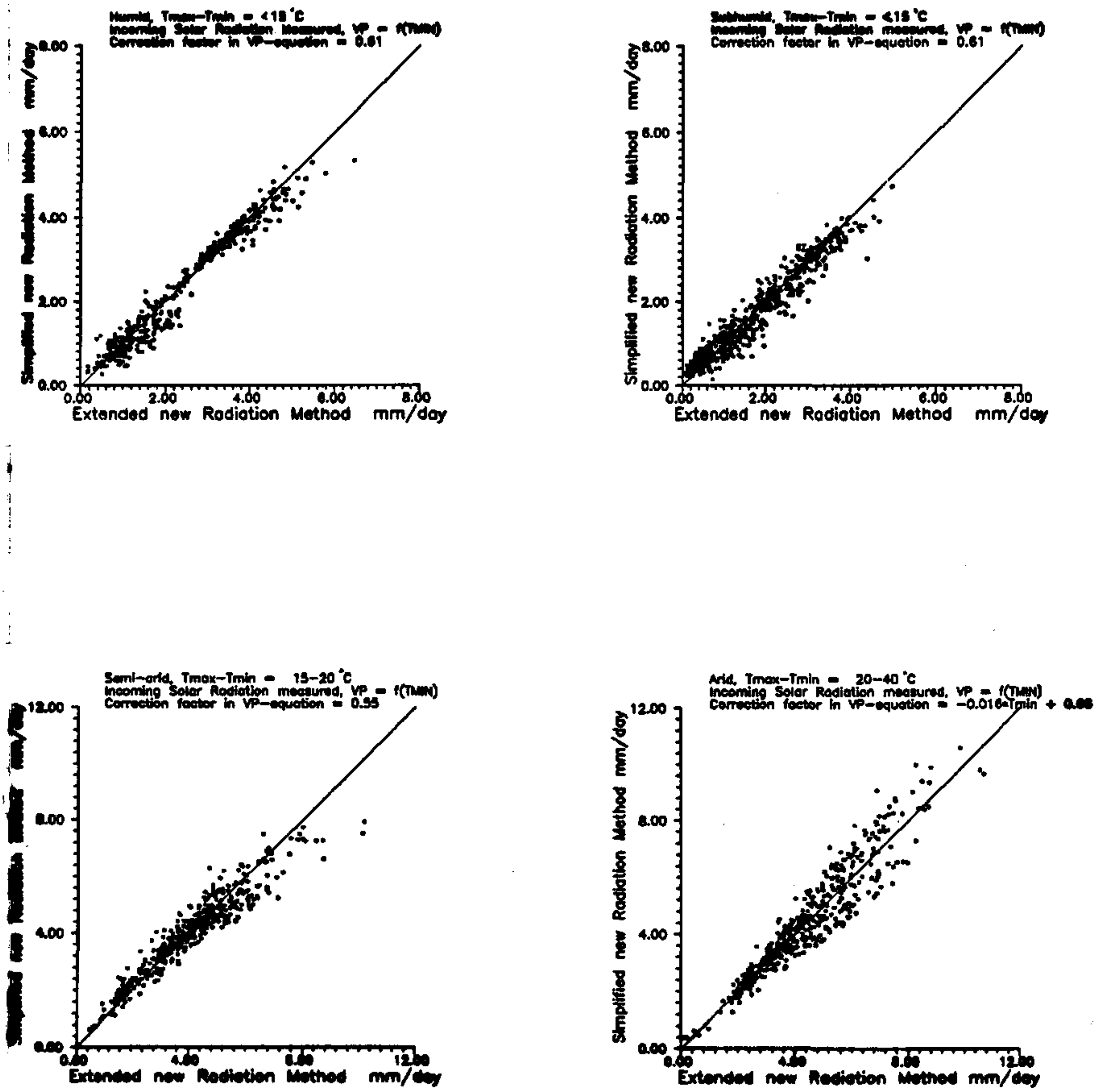


Fig. 3.2. Monthly potential evapotranspiration according to the Simplified new Radiation method versus the Extended new Radiation method for all four climate types. In all figures the 45°-line is given.

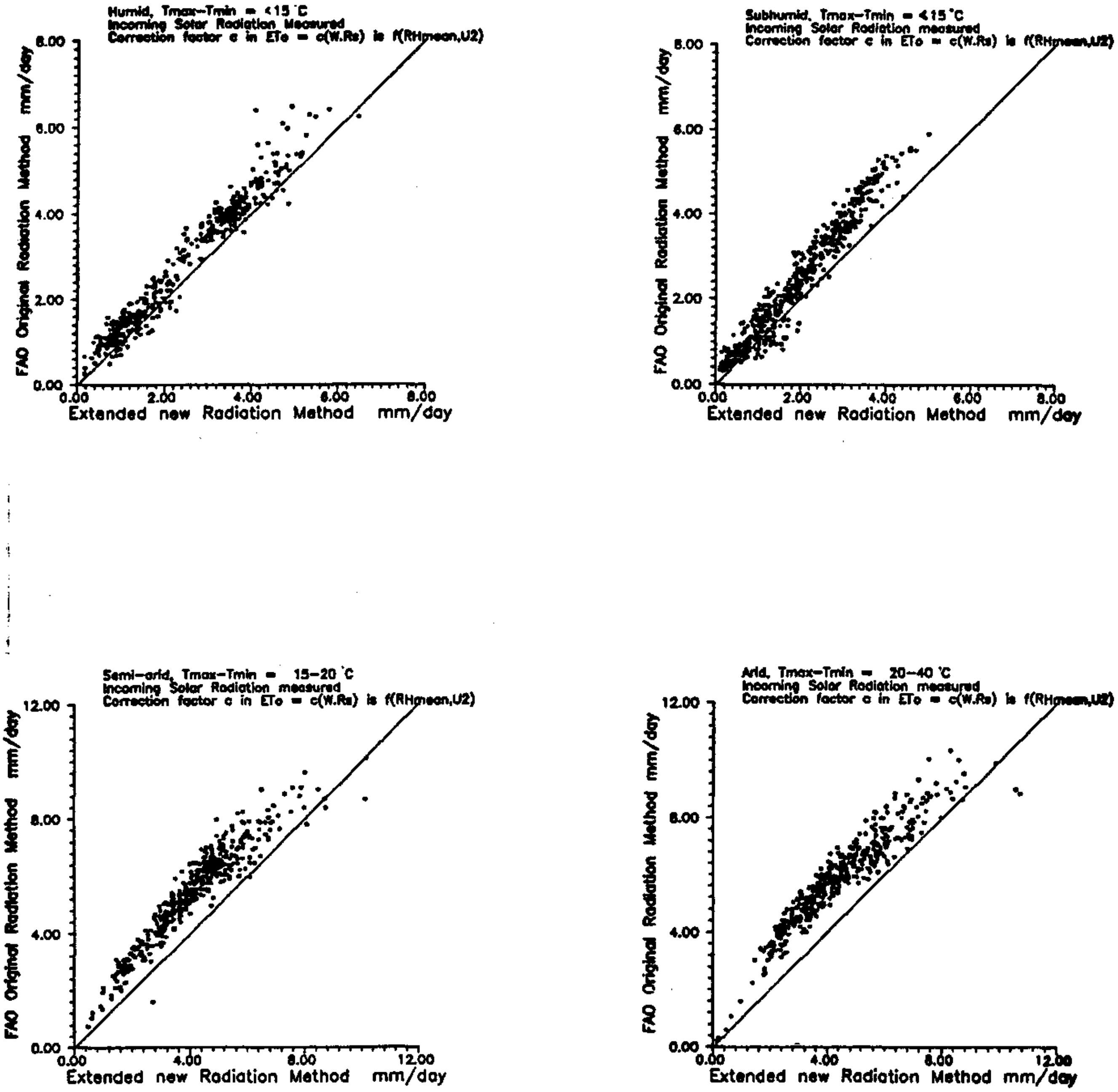


Fig. 3.3.a Monthly potential evapotranspiration according to the FAO Original Radiation method versus the Extended new Radiation method for all four climate types. In all figures the 45°-line is given.

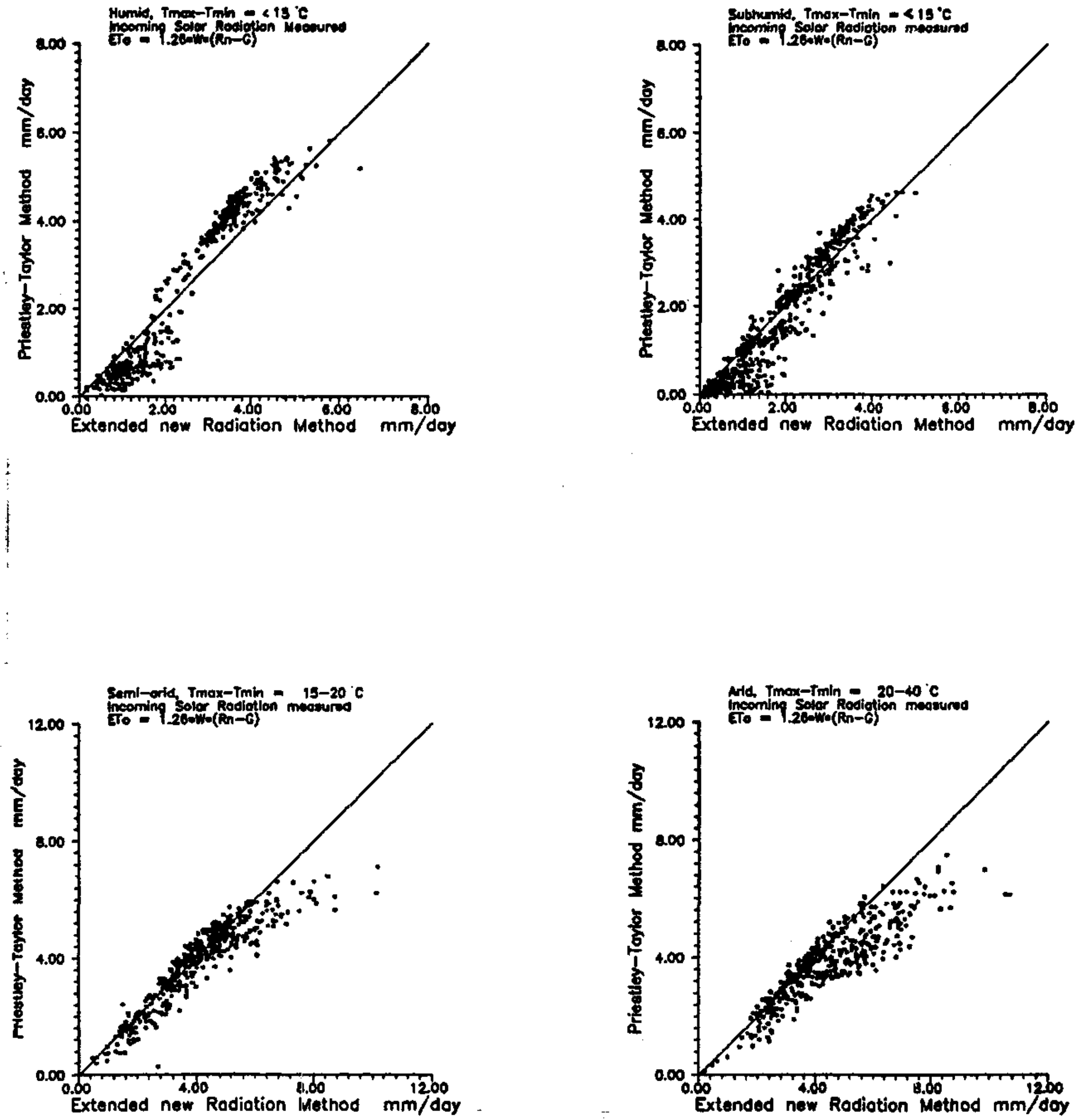


Fig. 3.3.b Monthly potential evapotranspiration according to the Priestly–Taylor method versus the Extended new Radiation method for all four climate types. In all figures the 45°-line is given.

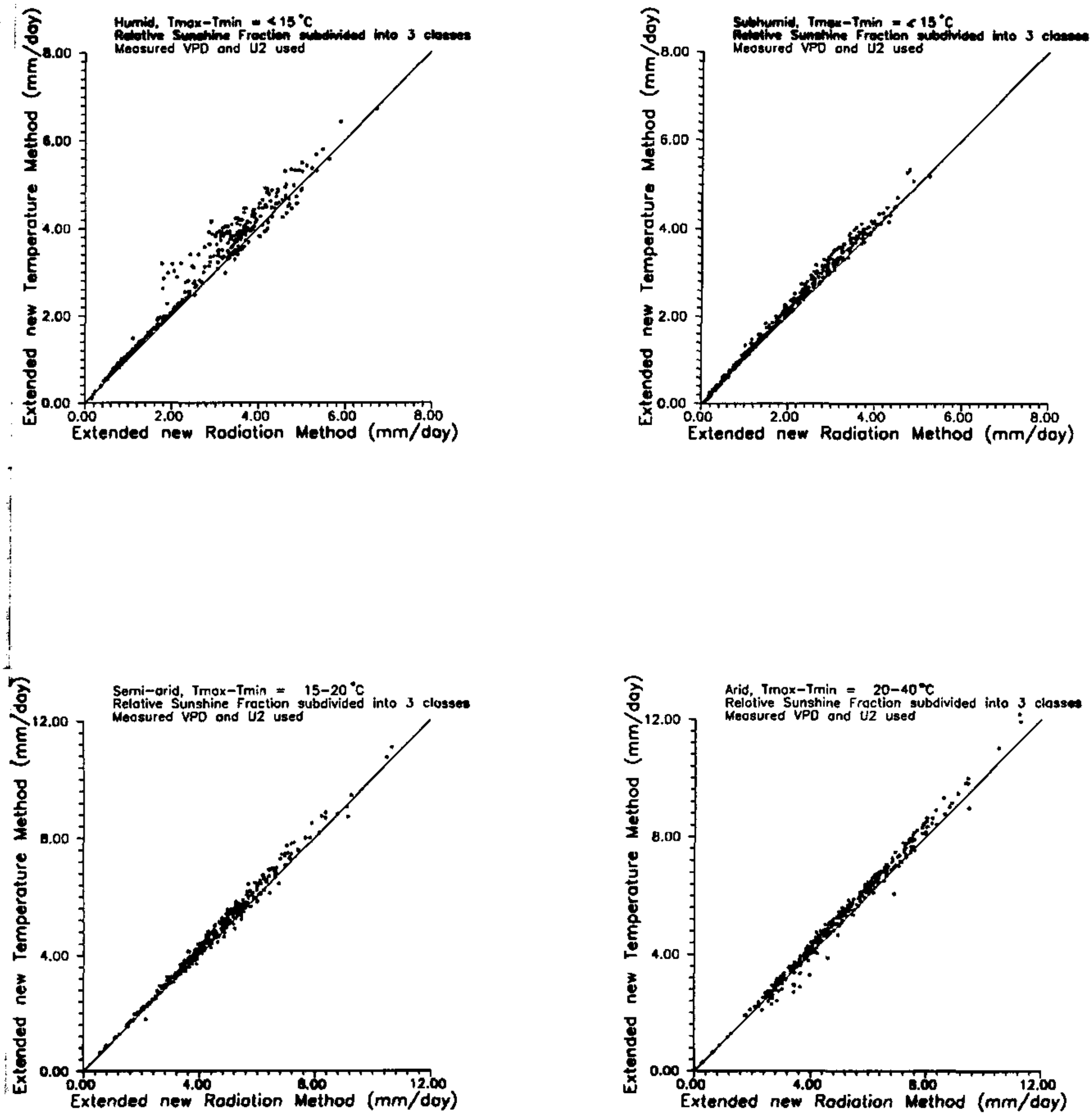


Fig. 3.4. Monthly potential evapotranspiration according to the Extended new Temperature method versus the Extended new Radiation method for all four climate types. In all figures the 45°-line is given.

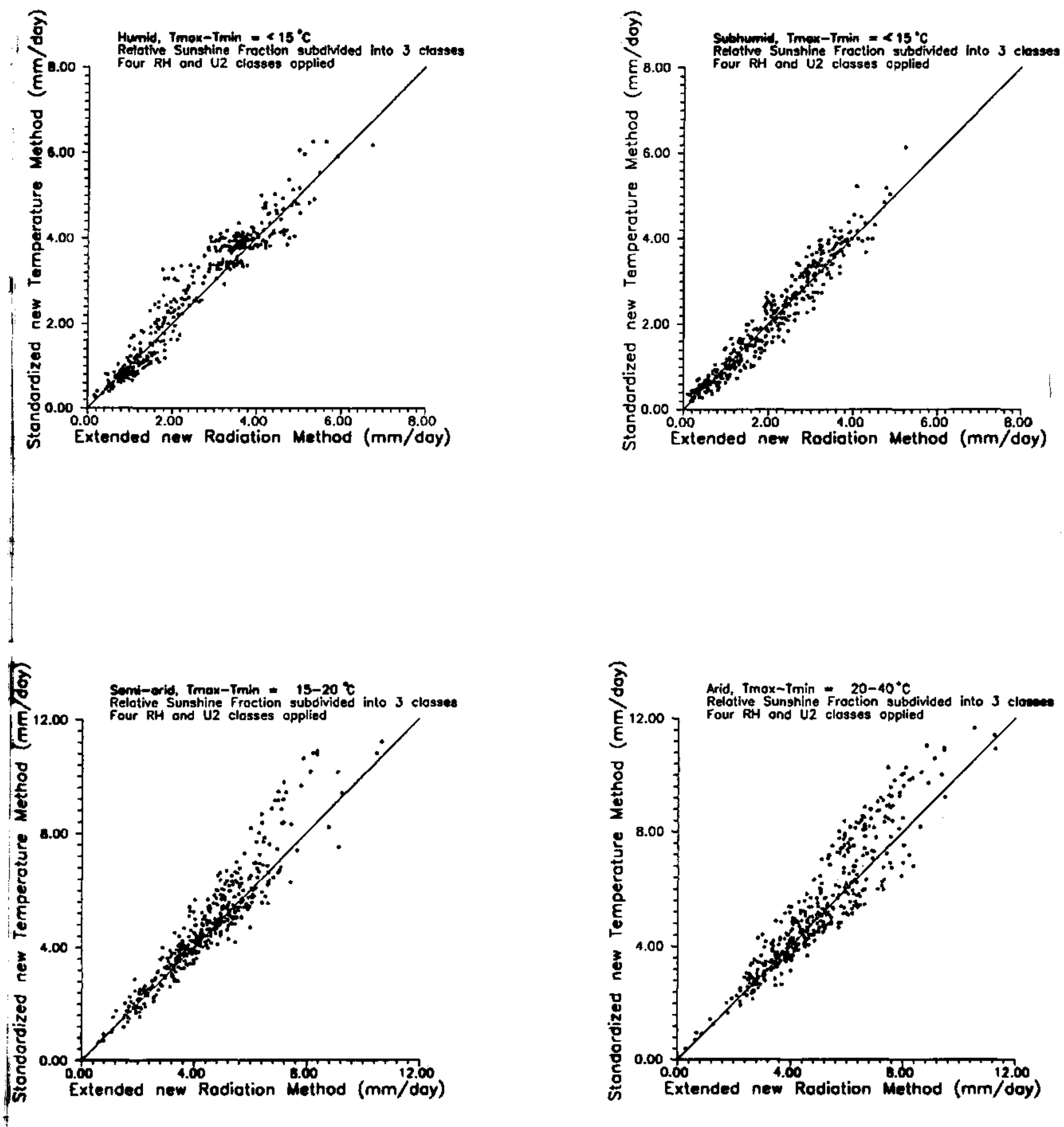


Fig. 3.5. Monthly potential evapotranspiration according to the Standardized new Temperature method versus the Extended new Radiation method for all four climate types. In all figures the 45°-line is given.

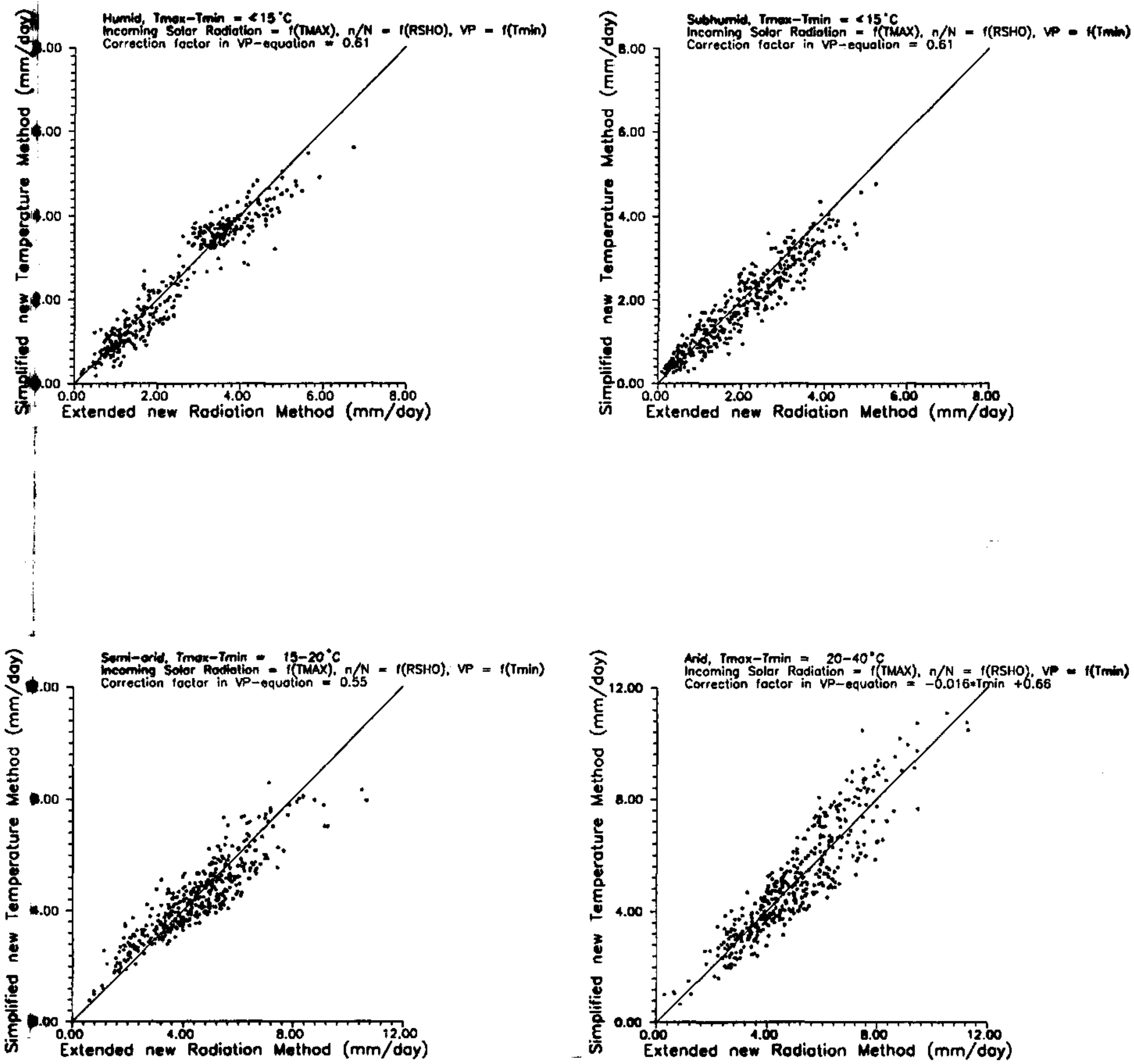


Fig. 3.6. Monthly potential evapotranspiration according to the Simplified new Temperature method versus the Extended new Radiation method for all four climate types. In all figures the 45°-line is given.

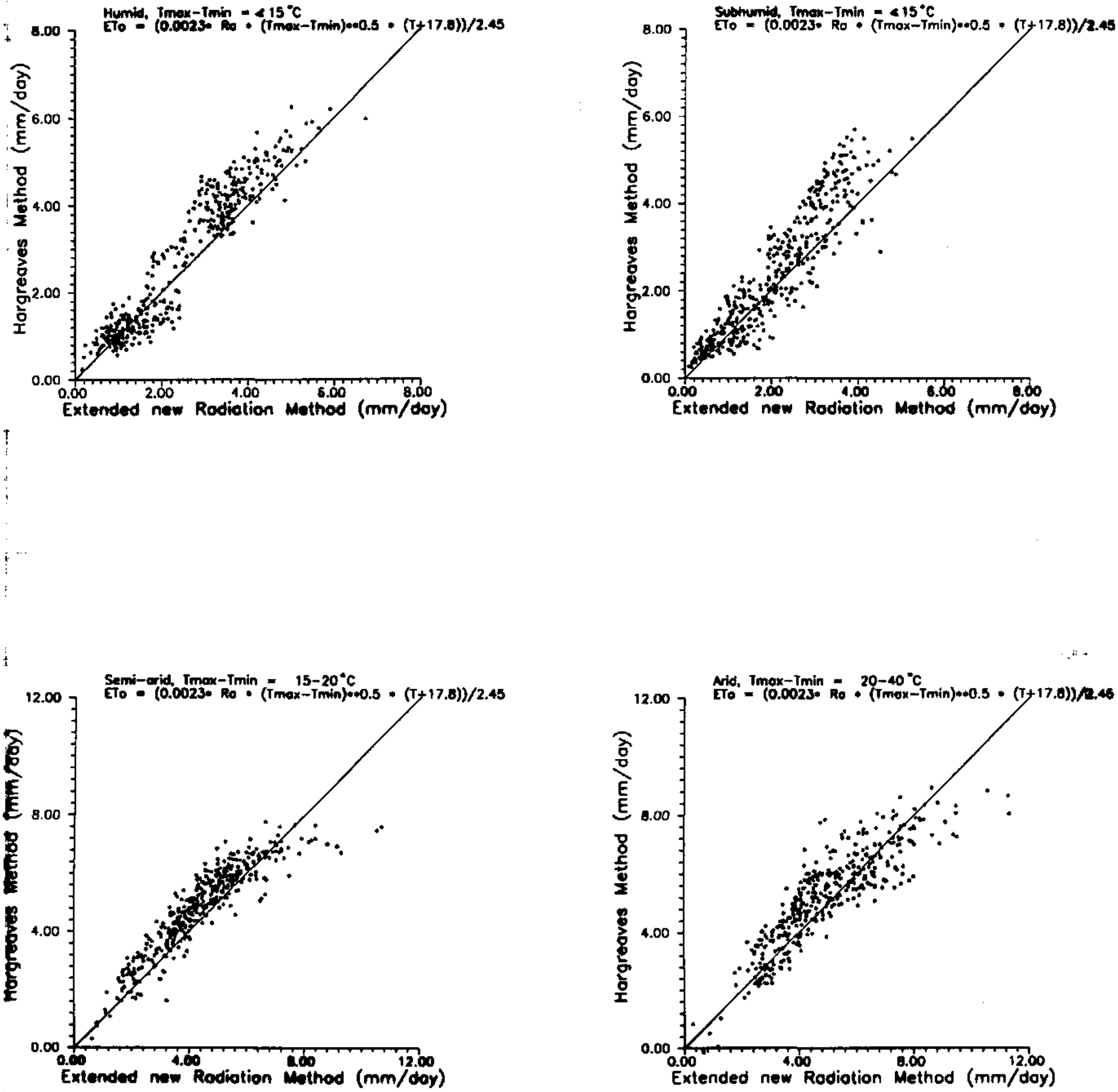


Fig. 3.7. Monthly potential evapotranspiration according to the Hargreaves method versus the Extended new Radiation method for all four climate types. In all figures the 45°-line is given.

All methods appear to be highly correlated with the Extended Radiation Method. This is indicated by the correlation coefficients in Table 3.4. The correlation coefficient alone, however, was considered to be insufficient in describing the goodness of fit of potential evapotranspiration estimates calculated with the Extended Radiation Method and the other methods. A high correlation does not exclude the possibility of a serious and consistent over- or underestimation.

Therefore an extra statistical parameter was introduced, which gives an indication of the average deviation of the points from the 45 degree line. The idea was adopted from Jensen, Burman and Allen (1990).
The so-called standard error of estimate (SEE) is described by the following equation.

$$SEE = \left[\frac{\sum_{i=1}^{n} (\hat{Y}_i - Y_i)^2}{n - 1} \right]^{0.5} \qquad (35)$$

Where $\hat{Y}_i$ is the potential evapotranspiration estimated by the standardized radiation method, the simplified radiation method, the FAO original radiation method, the Priestley-Taylor method, the extended temperature method, the standardized temperature method, the simplified temperature method or the Hargreaves method. Y_i refers to the calculations made with the extended radiation method. The number of points is given by n.
According to Jensen et al., SEE represents the maximum error in mm/day for 68 % of all estimates by a certain method, provided that the distribution of differences between RADEXT and other methods follows a normal distribution.

The calculation of the correlation coefficients and the standard error of estimate per method was conducted by the FORTRAN-program CORSEE.FOR. It is listed in Appendix 5.
This program needs the outputfile of PEVAP.FOR as input.

Table 3.4 summarizes the results for the 4 climate classes as subdivided on the basis of monthly rainfall amount.
Each climate class was represented by one arbitrarily chosen temperature difference class. In order to ensure realistic comparison n was taken the same for all climates and methods (n=430).

Table 3.4. Correlation coefficients and standard errors of estimate of various PET-estimates versus the extended Radiation Method. For the simplified radiation and temperature methods $e_d = C_f*f(T_{min})$. For the simplified Temperature Method $R_s = f(T_{max})$ and $n/N = f(R_s)$: method 1.

	Climate							
	Humid		Subhumid		Semi-arid		Arid	
Method	r	SEE	r	SEE	r	SEE	r	SEE
RADSTA	0.98	0.26	0.97	0.30	0.94	0.62	0.92	0.81
RADSIM	0.98	0.28	0.96	0.32	0.94	0.56	0.93	0.73
RADORI	0.98	0.50	0.97	0.64	0.93	1.42	0.92	1.57
RADPRI	0.96	0.63	0.95	0.52	0.91	0.81	0.88	1.32
TEMEXT	0.98	0.34	1.00	0.18	0.99	0.26	0.99	0.29
TEMSTA	0.97	0.40	0.97	0.30	0.94	0.70	0.93	0.89
TEMSIM	0.96	0.37	0.94	0.41	0.90	0.71	0.91	0.81
TEMHAR	0.95	0.58	0.92	0.66	0.91	0.78	0.88	0.89

3.2. Comparison of Radiation Methods

It appeared that for all climates the Standardized and Simplified Radiation methods were performing well. In case of the semi-arid and arid climate the simplified radiation equation yielded an even lower SEE-value than the standardized radiation method. This was probably because of errors caused by the crude discretization of relative humidity in the Standardized Radiation equation.
The mean maximum error in potential evapotranspiration for 68 % of all estimates was ranging from 0.27 mm/day for the humid climate to 0.77 for the arid climate.
SEE's being larger for arid than for humid locations is in accordance with the results found by Jensen et al.

It may be concluded that using an overall and constant coefficient per climate (except for the arid climate) leads to very satisfactorily results, which makes determination of various coefficients per area (coastal, mountainous ect.) a rather redundant operation.

The Original FAO Radiation method is in all cases rather high (r= 0.92-0.98) correlated to the extended radiation method. Inspection of Fig. 3.3 however, shows that this relation is characterized by a consistent overestimation of potential evapotranspiration by the original FAO radiation method in comparison with the calculations performed by Eq. (1) with measured values entered. This overestimation is indicated by high SEE-values and it increases in magnitude according as climate is getting drier.
The fact that Jensen et Al. found the original FAO radiation method to overestimate lysimetrically measured evapotrans-piration, might indicate that the PET-values as obtained by Eq. (1) are very close to reality.

The overestimation of the Original FAO Radiation method is caused by the fact that different weighting factors were used.
$W=\delta/(\delta+\gamma)$ and $1-W$ in stead of $\delta/(\delta+\gamma^*)$ and $\gamma/(\delta+\gamma^*)$. Furthermore, the original method does not incorporate longwave radiation and it uses a different aerodynamic term based on relative humidity and wind (2 m) and not on temperature.

The Priestley-Taylor method, which only uses a radiative term, leads to underestimations in the low evaporation region (PET < 2 mm/day) in the humid climates. The rest of the PET range is described sufficiently well. A slight tendency to overestimation exists in the higher PET region for the humid climates. The arid climate shows a consistent underestimation of PET values calculated by Priestley-Taylor as compared with the estimates of Eq. (1). In the semi-arid climate a deviation of the 45 degree line only occurs for estimates greater than 6 mm/day.

Comparison of these findings with the judgement of Jensen et Al. concerning the Priestley-Taylor Method (:"application of Priestley-Taylor leads to good **estimatons of measured PET in humid climates and** to underestimations in arid **climates", see Fig.** 3.8) **is again an indicative** of the excellent physically behaviour of **Eq.** (1).

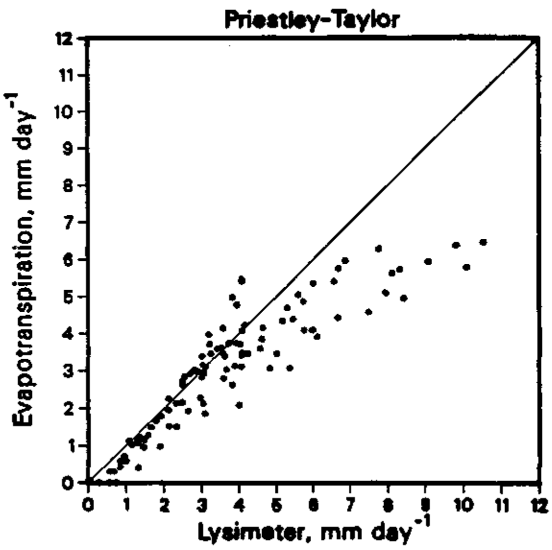


Fig. 3.8. **Estimates of PET by Priestley-Taylor** Method versus average monthly lysimeter **PET at 11 locations. From Jensen** et al. 1990.

In summary:the Extended Radiation method is highly correlated with the Standardized and the Simplified versions. This fact combined with the relatively small SEE-values, indicates that acceptance of these three Radiation methods is justified.

3.3. Comparison of Temperature Methods.

The Temperature methods on an average are slightly less correlated to the extended Radiation method as compared to the Radiation methods. On a whole, correlation decreases as the climate gets drier.

The **Extended Temperature** method, which uses 3 classes of n/N for calculation of short- and longwave radiation (see Eq. (3) and (4)) and applies measured e_d and U_2-values, has the best performance. In reality sampling of detailed moisture data combined with the non-availability of radiation measurements seems rather unlogical. This method was therefore only developed to illustrate the influence of replacement of a measured parameter (n/N) by several standardized values.

Application of only three n/N-classes yields very low SEE-values compared to the other methods, especially for the semi-arid and arid climate. This indicates that standardization of relative sunshine fraction is less drastic than standardization of relative humidity and wind speed, except for the humid climate. This result justifies the use of a limited amount of n/N-classes to estimate relative sunshine duration if no actual values are available. Maybe, even the use of only one standard value (for example 0.7) might lead to satisfactory results.

The **Standardized Temperature** method standardizes n/N, RH and U_2 by means of discrete classes. This operation yields lower r's and higher SEE's in comparison to the Extended Temperature method. Still, results are sufficiently good to use this simpler method in stead of the exacting formula 1.

Application of Eq. (1) with empirically derived values of e_d and R_s, and estimations of U_2 leads to the so-called **Simplified Temperature method**. In this case R_s was estimated from T_{max}. It appears that this method gives lower SEE-values in the humid and arid case as compared to the Standardized Temperature method. A similar result was found for the simplified Radiation method for semi-arid and arid climates.
For the subhumid and semi-arid climate classes performance by the Simplified method was only slightly worse, which implies that this method is promising in providing a physically-based alternative of the Combination Method (Eq. (1)).

Still, it has to be remembered that most global radiation values of the original FAO data set were not measured but calculated from the relative sunshine fraction and 3 pairs of Angström values.

The **Hargreaves method**, which calculates PET as a function of R_a, T_{avg} and T_{max}-T_{min} is in all cases a worse estimator of PET compared to the Temperature methods derived from Eq. (1).
(r-values are lower, wheras SEE-values are higher).
In the more arid climates the performance of the Hargreaves method is getting close to that of the TEMEXT-, TEMSTA- and TEMSIM-methods.
The still rather good performance of this simple method is achieved by the fact that the variables in this formula were directly calibrated with grass reference evapotranspiration. This compared to pursuing simplification of a complicated formula like Eq.(1) by relating the various parts of this formula to meteorological parameters, in which each simplification might imply an extra error.

3.4. Comparison of Alternative Simplified Temperature Methods.

Using a direct relation between relative sunshine fraction and maximum temperature (method 2) gives equal or slightly higher correlation coefficients and **lower** SEE-values, except for the humid climate, compared to those of method 1. This in indicated by Table 3.5.

Table 3.5. Correlation coefficients and standard errors of estimate of simplified Temperature method versus the extended Radiation Method.
$e_d = C_f*f(T_{min})$. $n/N = f(T_{max})$. $R_s = f(n/N)$: method 2.

	Climate							
	Humid		Subhumid		Semi-arid		Arid	
Method	r	SEE	r	SEE	r	SEE	r	SEE
TEMSIM	0.96	0.41	0.95	0.34	0.92	0.66	0.92	0.77

So it seems that determination of n/N from T_{max} and calculation of R_s from this value, gives better estimates of PET than method 2. This was not expected if we recall the more scattered appearance of the graphical representation of n/N as a function of T_{max} compared to R_s as a function of T_{max}. (Figs. 2.13 and 2.14).
Performance is only slightly better, but because this method will appear more logical to the users is should be prefered above Method 1.

Fig. 3.9 gives the PET for the humid climate as estimated by the Simplified new Temperature method applying method 2 to calculate n/N.

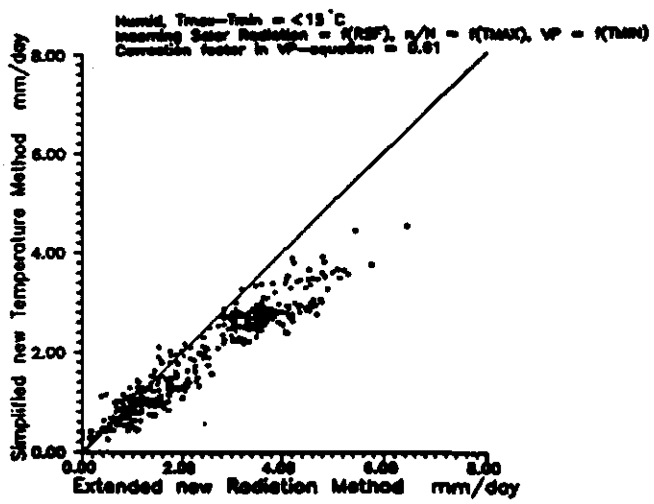


Fig. 3.9. PET-estimates of Simplified new Temperature method versus those of the Extended new Radiation method when relative sunshine fraction (n/N) is assumed to be a function of maximum temperature (T_{max}). Climate Class is H15.

In the case of the humid climates, calculation of incoming global radiation with a relationship depending on RH (method 3) leads to serious overestimation in the low evaporation regions, whereas PET is underestimated under more arid conditions. An example of this is given by Fig. 3.10.
Table 3.6 gives the correlation coefficients and standard errors of estimates for the 4 climate types if method 3 was used to obtain values of global incoming **radiation**.

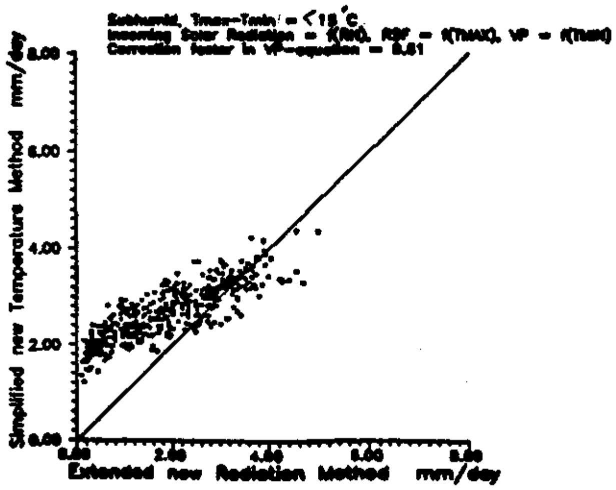


Fig. 3.10. **PET-estimates of Simplified new Temperature** method versus those of the Extended **new Radiation method with a RH-dependent relationship** for global radiation (R_s) estimates. Climate Class is SH15.

Table 3.6. Correlation coefficients and standard errors of estimate of simplified Temperature method versus the extended Radiation Method. $e_d = C_f*f(T_{min})$. $R_s = f(RH)$. $n/N = f(T_{max})$: method 3.

	Climate							
	Humid		Subhumid		Semi-arid		Arid	
Method	r	SEE	r	SEE	r	SEE	r	SEE
TEMSIM	0.82	0.97	0.84	1.12	0.81	1.02	0.87	0.89

It appeared that method 3 gives better results as climate is getting dryer. In these cases relative humidity is a rather good descriptor of incoming solar radiation.

Using formulas to calculate vapour pressure like;

$$e_d = (a*e_a(T_{avg}) - \gamma*(T_{max}-T_{min}) + b)/10.0 \qquad (36)$$

seem promising in the more arid climates. In the humid climates however, such a relationship may result in severe overestimations of PET-estimates. See Fig. 3.11.
However, more investigation has to be conducted to test the usefulness of this kind of equation.

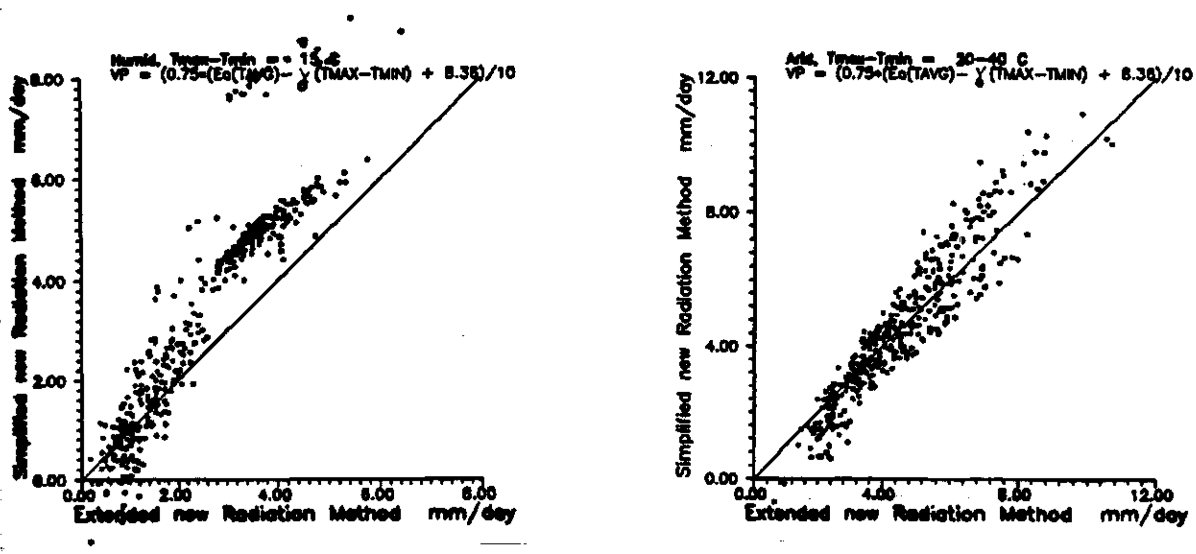


Fig. 3.11. PET-estimates of Simplified new Radiation method versus those of the Extended new Radiation method when vapour pressure is assumed to be a function of E_a, γ and $T_{max}-T_{min}$. Climate Classes are H15 and A2040, respectively.

4. CONCLUSIONS

* It is not justified to correlate T_{max}-T_{min}, divided into small intervals, with certain meteorological parameters.
Temperature difference (T_{max}-T_{min}) has to be considered as a sort of rough humidity indicator, like in the Hargreaves method.

* **Actual vapour pressure** can be derived from minimum temperature by application of Eq. (14) combined with overall coefficients C_f per climate.

* It appeared that for all climatic classes, relationship could be detected between **maximum temperature and relative sunshine fraction and incoming global radiation**, respectively.

* The Standardized and Simplified **Radiation** methods, based on Eq. (1) can be used without hesitation for all climate classes. High correlation coefficients and small SEE-values occur if these methods are correlated to Eq. (1) which uses only measured parameters as input.

* The rather small errors indicate that the dependence of the overall coefficient on site-specific characteristics is of little influence on the final potential evapotranspiration calculated. This implies that there is no **direct need for determination of individual coefficients for certain geographical areas**. In fact it would be better not to do so as the zones with deviating climatic conditions certainly can not be generalized.

* The **Original FAO Radiation** method gives an overestimation of PET as compared to the newly introduced Eq. (1). This is mainly caused by different weighting factors and the absence of longwave radiation in the Radiation term of the original method. According to previous authors the Original method is overestimating real PET. This means that the new Combination Method may perform better in describing actually measured PET than previous methods.

* The **Priestley-Taylor** method deviates from the Combination Method (Eq. (1)) for the semi-arid and arid climates. This fact was already recorded by other authors (e.g. Jensen et al.).

* The **Standardized and Simplified Temperature** methods, derived from Formula 1, are useful alternatives for the extended new Radiation method. Provided however, that method 2 (or possibly method 1) of Table 3.3 (**relative sunshine fraction is assumed to be a function of maximum temperature**) is used to estimate global incoming radiation. The simplified temperature method works relatively better in the semi-arid and arid climates, although SEE-values increase as compared to the humid climates.

Calculation of **global incoming radiation from maximum temperature**, and application of these values to subsequently estimate relative sunshine fraction leads to higher standard errors of estimate. Correlation coefficients stay about the same. It may be concluded that this option is inferior to relating n/N directly to maximum temperature.

Taking **global incoming radiation as a function of relative humidity** (method 3 of **Table** 3.3) **decreases correlation-values considerably**. For the humid and subhumid climates SEE is doubled. The semi-arid and arid climates show less increase of SEE-values, which indicates the possible usefulness of 'method 3' in arid regions.

* The **Hargreaves** method gives satisfactory results in the humid, subhumid and semi-arid climates. Hargreaves SEE's are lhigher than SEE-values for the Simplified Temperature method. For the arid climate the method starts to deviate considerably in the higher PET region.

Usefulness of new Simplified Temperature method:

The Simplified new Temperature method has one disadvantage in comparison to the well-known Hargreaves method. The simplified FAO method asks for much more calculations, which have to be supplied by the users (global radiation, relative sunshine fraction, extraterrestial radiation, longwave radiation, actual vapour pressure, average temperature, saturated vapour pressure and an estimation of windspeed). This compared to input for the Hargreaves equation of extraterrestial radiation, T_{max}-T_{min} and T_{avg} only, makes the newly developed Temperature method rather bulky and not so userfriendly. Supply of tables and figures might improve the usefulness of the method.

The fact that the simple Hargreaves method was developed by directly relating certain parameters to potential evapotranspiration makes that its performance is only slightly worse in comparison to the other Temperature Methods. The average temperature combined with the extraterrestial radiation is an indicator of global incoming radiation, wheras T_{max}-T_{min} is related to relative humidity.

Literature

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APPENDIX 1.

PEVAP.FOR, a program to calculate potential evapotranspiration according to various methods.

```
      PROGRAM PEVAP

C*************************************************************
C This program calculates reference crop evapotranspiration   *
C according to several calculation methods.                   *
C The methods can be subdivided into two groups:              *
C                                                             *
C - 1. Radiation methods                                      *
C - 2. Temperature methods                                    *
C                                                             *
C   1.a Extended new FAO-Radiation method                     *
C   1.b Standardized new FAO-Radiation method                 *
C   1.c Simplified new FAO-Radiation method                   *
C   1.d Original FAO-Radiation method                         *
C   1.e Priestley-Taylor method                               *
C                                                             *
C   2.a Extended new FAO-Temperature method                   *
C   2.b Standardized new FAO-Temperature method               *
C   2.c Simplified new FAO-Temperature method                 *
C   2.d Hargreaves method                                     *
C                                                             *
C   Potential evapotranspiration can be calculated for        *
C   various Climate Classes which have to be characterized    *
C   by monthly amount of rainfall and monthly temperature     *
C   difference (TMAX-TMIN)                                    *
C   Possible options are given below.                         *
C                                                             *
C   CCLASS = 1: HUMID     : > 150 mm                          *
C   CCLASS = 2: SUBHUMID  : 70-150 mm                         *
C   CCLASS = 3: SEMIARID  : 20-70 mm                          *
C   CCLASS = 4: ARID      : < 20 mm                           *
C                                                             *
C   TEMCLAS = 1: < 15 C                                       *
C   TEMCLAS = 2: 15 - 20 C                                    *
C   TEMCLAS = 3: 20 - 40 C                                    *
C                                                             *
C   METHOD  = 1: RSHO = f(TMAX), RSF = f(RSHO)                *
C             2: RSF = f(TMAX), RSHO = f(RSF)                 *
C             3: RSHO = f(RH), RSF = f(TMAX)                  *
C                                                             *
C Author: Anne Verhoef                                        *
C Adress: Department of Hydrology,Soil Physics and Hydraulics *
C         Nieuwe Kanaal 11                                    *
C         6709 PA Wageningen                                  *
C         The Netherlands                                     *
C Date  : March 1991                                          *
C By order of FAO, Rome, Italy                                *
C*************************************************************
```

```
      INTEGER MO,N,Z,J,CCLASS
      INTEGER TEMCLAS,METHOD
      REAL RSHO,RNSHO,RSF,RA,EPS,ED,RNLON,TMAX,TMIN,RNET,
     . EA,T,TK,P,DELTA,GAMMA,GAMMAK,U2,U2M,RATERM,RH,RHMEAN,VPD,
     . AETERM,RADEXT,RADSTA,RADSIM,LABDA,LAT,LONG,TKMAX,TKMIN,
     . STATNR,W,C,RS,RADRAD,OMEGA,DEL,DR,PHI,TEMEXT,RSMEAN,
     . TEMSTA,TEMHAR,TEMSIM,TAVG,RAIN,DELT,VP,VPDM,
     . A,B,EAMIN,EAMAX
      CHARACTER INPUT*30,OUTPUT*30
      DATA G/0.0/,ALPHA/0.23/,asn/0.25/,bsn/0.50/
      DATA SIGMA/4.903E-9/,labda/2.45/

******************************
*--- Initial section---
******************************

* Open inputfile
      WRITE(*,'(A$)') ' ENTER NAME INPUTFILE:'
      READ(*,'(A)') INPUT
      WRITE(*,'(A$)') ' ENTER NAME OUTPUTFILE:'
      READ(*,'(A)') OUTPUT
      WRITE(*,'(A$)') ' GIVE CLIMATE CLASS:'
      READ(*,*) CCLASS
      WRITE(*,'(A$)') ' GIVE TEMPERATURE DIFFERENCE CLASS:'
      READ(*,*) TEMCLAS
      WRITE(*,'(A$)') 'GIVE METHOD FOR CALCULATION OF RSHO:'
      READ(*,*) METHOD
      OPEN(40,FILE=INPUT,STATUS='OLD')

      N=0
5     CONTINUE
* Read input parameters per station from inputfile

      READ(40,*)STATNR,LAT,LONG,Z,MO,TAVG,RAIN,TMAX,TMIN,DELT,RSF,VP,
     .VPDM,RH,RSHO,U2M


      N=N+1

* Open output file

      OPEN(41,FILE=OUTPUT,STATUS='UNKNOWN')


******************************
*--- Initial calculations---
******************************
        TKMAX=TMAX+273.16
        TKMIN=TMIN+273.16

        T  = (TMAX+TMIN)/2
        TK = T + 273.16
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C       1.a  Extended new FAO-Radiation method        C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

***********************************************
*    A. THE RADIATION TERM
***********************************************
*------ Calculation of net radiation-----------
***********************************************

*        1. SHORTWAVE RADIATION

*        RNSHO - net short wave radiation [MJ/m2/d]
*        ALPHA - canopy reflection coefficient
*                0.23 overall average for grass
*        RSHO  - incoming solar radiation [MJ/m2/d]
*        RSF   - relative sunshine fraction (n/N)
*        n     = bright sunshine hours per day [hr]
*        N     - total daylength [hr]


*-------Direct input of global radiation RSHO
*------ Net short wave radiation:

       RNSHO = (1-ALPHA)*RSHO

*        2. LONGWAVE RADIATION

*        RNLON - net longwave radiation [MJ/m2/d]
*        RSF   - relative sunshine fraction (n/N)
*        n     - bright sunshine hours per day [hr]
*        N     = total daylength [hr]
*        EPS   - net emissivity

C------ Parameterization of emissivity according to Idso and
C------ Jackson (1969)

      EPS - -0.02+0.261*EXP(-7.77E-4*T**2)
      RNLON - (0.9*(RSF/100)+0.1)*EPS*SIGMA*
     .        ((TKMAX**4+TKMIN**4)/2.0)

*-------Calculation of RNET, the net radiation------------

      RNET = RNSHO-RNLON

*-------RNET in MJ/m2/d -----> RNET in mm/d----------------

      RNET - RNET/2.45
```

```
*------ Calculation of other parameters and variables relevant
*------ for radiation and aerodynamic term

*       EA      - saturation vapour pressure [kPa]
*       T       - temperature [°C]
*       TK      - temperature [°K]
*       P       - atmospheric pressure at elevation z [kPa]
*       Z       - elevation above reference [m]
*       DELTA   - slope vapour pressure [kPa/°C]
*       GAMMA   - psychrometric constant [kPa/°C]
*       GAMMAK  - corrected psychrometric constant [kPa/°C]
*       U2M     - measured windspeed at reference level [m/s]

      EAMIN - 0.6108 * EXP((17.27*TMIN)/(TMIN+237.3))
      EAMAX - 0.6108 * EXP((17.27*TMAX)/(TMAX+237.3))
      EA - (EAMIN+EAMAX)/2.0
      P - 101.3*((TK-0.0065*Z)/TK)**5.256

      DELTA - (4098*EA)/((T+237.3)**2)
      GAMMA - 1.6286E-3*(P/LABDA)
      GAMMAK - GAMMA*(1+0.347*U2M)

*------ Final calculation of radiation term


      RATERM - (DELTA/(DELTA+GAMMAK))*(RNET-G)


*---------- Final calculation of aerodynamic term

      AETERM - (GAMMA/(DELTA+GAMMAK))*(936.3/(T+274.3))*
     .              U2M*VPDM


*----------Final calculation of reference evapotranspiration


      RADEXT - RATERM + AETERM
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     1.b. Standardized new FAO-Radiation method       C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC


*    A. THE RADIATION TERM
**********************************************
*----- Calculation of net radiation-----------
**********************************************


*-------Incoming solar radiation is measured
*-------Net shortwave Radiation

        RNSHO = (1-ALPHA)*RSHO


C----- Parameterization of emissivity according to Idso and
C----- Jackson (1969)

       EPS = -0.02+0.261*EXP(-7.77E-4*T**2)

       RNLON = (0.9*(RSF/100)+0.1)*EPS*SIGMA*
      . ((TKMAX**4+TKMIN**4)/2.0)

*-------Final calculation of RNET, the net radiation-----------

       RNET = RNSHO-RNLON

*-------RNET in MJ/m2/d -----> RNET in mm/d---------------

       RNET = RNET/2.45

*----- Calculation of other parameters and variables relevant
*----- for radiation and aerodynamic term

       EAMIN = 0.6108 * EXP((17.27*TMIN)/(TMIN+237.3))
       EAMAX = 0.6108 * EXP((17.27*TMAX)/(TMAX+237.3))
       EA = (EAMIN+EAMAX)/2.0
       P = 101.3*((TK-0.0065*Z)/TK)**5.256

       DELTA = (4098*EA)/((T+237.3)**2)
       GAMMA = 1.6286E-3*(P/LABDA)

**********************************************************
*-------1. Standardization of VPD and wind values
**********************************************************
*  The aerodynamic term is standardized for several general
*  levels of mean relative humidity. Relative humidity can
*  be classified as follows.
*  RHMEAN low          : <40 %  ,25 % used in model.
*  RHMEAN low-medium   : 40-55 %,48 % used in model.
*  RHMEAN medium-high  : 55-70 %,63 % used in model.
*  RHMEAN high         : >70 %  ,85 % used in model.
*  With these standardized values of RHMEAN the vapour pressure
*  at dewpoint can be calculated;
```

```
      IF(RH.LT.40.0) THEN
        RHMEAN = 25.0
      ELSEIF (RH.GE.40.0.AND.RH.LT.55.0) THEN
        RHMEAN = 48.0
      ELSEIF (RH.GE.55.0.AND.RH.LT.70.0) THEN
        RHMEAN = 63.0
      ELSEIF (RH.GT.70.0) THEN
        RHMEAN = 85.0
      ENDIF

      ED = EA*(RHMEAN/100.0)
      VPD = EA-ED

C  For the daytime wind (07.00-19.00 hours) values the following
C  classification is applied.
C  U2 low               : 0-2 m/s, 1.0 m/s used in model.
C  U2 moderate          : 2-5 m/s, 3.5 m/s used in model.
C  U2 high              : 5-8 m/s, 6.5 m/s used in model.
C  U2 very high         : >8 m/s ,10.0 m/s used in model.

      IF(U2M.LT.2.0) THEN
        U2 = 1.0
      ELSEIF (U2M.GE.2.0.AND.U2M.LT.5.0) THEN
        U2 = 3.5
      ELSEIF (U2M.GE.5.0.AND.U2M.LT.8.0) THEN
        U2 = 6.5
      ELSEIF (U2M.GT.8.0) THEN
        U2 = 10.0
      ENDIF

      GAMMAK = GAMMA*(1+0.347*U2)

*----- Final calculation of radiation term


      RATERM = (DELTA/(DELTA+GAMMAK))*(RNET-G)

*-------- Final calculation of aerodynamic term

      AETERM = (GAMMA/(DELTA+GAMMAK))*(936.3/(T+274.3))*
     .                U2*VPD


*---------Final calculation of reference evapotranspiration


      RADSTA = RATERM + AETERM
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     1.c. Simplified new FAO-Radiation method     C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC


*    A. THE RADIATION TERM
***********************************************
*----- Calculation of net radiation-----------
***********************************************


*-------Incoming solar radiation is measured

       RNSHO = (1-ALPHA)*RSHO


C----- Parameterization of emissivity according to Idso and
C----- Jackson (1969)

      EPS = -0.02+0.261*EXP(-7.77E-4*T**2)

      RNLON = (0.9*(RSF/100)+0.1)*EPS*SIGMA*
     . ((TKMAX**4+TKMIN**4)/2.0)

*-------Final calculation of RNET, the net radiation------------

      RNET = RNSHO-RNLON

*-------RNET in MJ/m2/d -----> RNET in mm/d---------------

      RNET = RNET/2.45

*----- Calculation of other parameters and variables relevant
*----- for radiation and aerodynamic term

      EAMIN = 0.6108 * EXP((17.27*TMIN)/(TMIN+237.3))
      EAMAX = 0.6108 * EXP((17.27*TMAX)/(TMAX+237.3))
      EA = (EAMIN+EAMAX)/2.0
      P = 101.3*((TK-0.0065*Z)/TK)**5.256

      DELTA = (4098*EA)/((T+237.3)**2)
      GAMMA = 1.6286E-3*(P/LABDA)

*************************************************************
*-------1. Simplification of Vapour Pressure
*************************************************************
       IF(CCLASS.EQ.1) THEN
         CORFAC=0.61
       ELSEIF(CCLASS.EQ.2) THEN
         CORFAC=0.61
       ELSEIF(CCLASS.EQ.3) THEN
         CORFAC=0.55
       ELSEIF(CCLASS.EQ.4) THEN
         CORFAC=-0.016*TMIN+0.66
       ENDIF
```

```
      ED = CORFAC * EXP((17.27*TMIN)/(TMIN+237.3))

      VPD = EA-ED

************************************************************
*------- Standardization of wind values                    *
************************************************************
C  For the daytime wind (07.00-19.00 hours) values the following
C  classification is applied.
C  U2 low              : 0-2 m/s, 1.0 m/s used in model.
C  U2 moderate         : 2-5 m/s, 3.5 m/s used in model.
C  U2 high             : 5-8 m/s, 6.5 m/s used in model.
C  U2 very high        : >8 m/s  ,10.0 m/s used in model.

       IF(U2M.LT.2.0) THEN
         U2 = 1.0
       ELSEIF (U2M.GE.2.0.AND.U2M.LT.5.0) THEN
         U2 = 3.5
       ELSEIF (U2M.GE.5.0.AND.U2M.LT.8.0) THEN
         U2 = 6.5
       ELSEIF (U2M.GT.8.0) THEN
         U2 = 10.0
       ENDIF

      GAMMAK = GAMMA*(1+0.347*U2)

*------ Final calculation of radiation term


      RATERM = (DELTA/(DELTA+GAMMAK))*(RNET-G)

*--------- Final calculation of aerodynamic term

      AETERM = (GAMMA/(DELTA+GAMMAK))*(936.3/(T+274.3))*
     .              U2*VPD


*---------Final calculation of reference evapotranspiration


      RADSIM = RATERM + AETERM
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     1.d Original FAO-Radiation method                          C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

*--------This method can be described by the formula ETo=c(W.Rs)

      P = 101.3*((TK-0.0065*Z)/TK)**5.256

      EAMIN = 0.6108 * EXP((17.27*TMIN)/(TMIN+237.3))
      EAMAX = 0.6108 * EXP((17.27*TMAX)/(TMAX+237.3))
      EA = (EAMIN+EAMAX)/2.0
      DELTA = (4098*EA)/((T+237.3)**2)
      GAMMA = 1.6286E-3*(P/LABDA)
      RS = RSHO/2.45
      W = DELTA/(DELTA+GAMMA)
      C =1.066 - 0.0013*RHMEAN + 0.045*U2M -0.0002*RHMEAN*U2M-
     .   0.0000315*RHMEAN**2 - 0.0011*U2M**2

      RADRAD=C*(W*RS)

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C       1.e  Priestley Taylor equation                           C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

*-------This method is described by the formula ETo=1.26*W.*(Rn-G)

      P = 101.3*((TK-0.0065*Z)/TK)**5.256

      EAMIN = 0.6108 * EXP((17.27*TMIN)/(TMIN+237.3))
      EAMAX = 0.6108 * EXP((17.27*TMAX)/(TMAX+237.3))
      EA = (EAMIN+EAMAX)/2.0
      DELTA = (4098*EA)/((T+237.3)**2)
      GAMMA = 1.6286E-3*(P/LABDA)
      W = DELTA/(DELTA+GAMMA)

      RNSHO = (1-ALPHA)*RSHO


C------ Parameterization of emissivity according to Idso and
C------ Jackson (1969)

      EPS = -0.02+0.261*EXP(-7.77E-4*T**2)

      RNLON = (0.9*(RSF/100)+0.1)*EPS*SIGMA*
     . ((TKMAX**4+TKMIN**4)/2.0)

*-------Final calculation of RNET, the net radiation-------------

      RNET = RNSHO-RNLON

*-------RNET in MJ/m2.d ------> RNET in mm/d-----------------

      RNET = RNET/2.45

      RADPRI = 1.26*W*RNET
```

```
****************************************************************
*                     TEMPERATURE METHODS                       *
****************************************************************

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C   2.a Extended new FAO-Temperature method                    C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

*-------Standardization of Relative Sunshine Fraction only

       IF(RSF.LT.60.0) THEN
         RSMEAN = 0.45
       ELSEIF(RSF.GE.60.AND.RSF.LT.80) THEN
         RSMEAN = 0.70
       ELSEIF(RSF.GE.80) THEN
         RSMEAN = 0.90
       ENDIF

*-------Calculation of extraterrestial radiation, Ra

       PHI = (LAT/360)*2*3.1416
       J = INT(30.42*MO-15.23)
       DR = 1 + 0.033 * COS(((2*3.1416)/365)*J)
       DEL = 0.4093*SIN(((2*3.1416)*(284+J))/365)
       OMEGA= ACOS(-TAN(PHI)*TAN(DEL))

       RA = 37.586*DR*(OMEGA*SIN(PHI)*SIN(DEL)
     .      + COS(PHI)*COS(DEL)*SIN(OMEGA))



       RSHO = (ASN + (BSN*RSMEAN))*RA
       RNSHO = (1-ALPHA)*RSHO

C----- Parameterization of emissivity according to Idso and
C----- Jackson (1969)

      EPS = -0.02+0.261*EXP(-7.77E-4*T**2)

      RNLON = (0.9*RSMEAN+0.1)*EPS*SIGMA*
     .        ((TKMAX**4+TKMIN**4)/2.0)


*------Calculation of RNET, the net radiation-----------

      RNET = RNSHO-RNLON

*-------RNET in MJ/m2.d -----> RNET in mm/d---------------

      RNET = RNET/2.45

*----- Calculation of other parameters and variables relevant
*----- for radiation and aerodynamic term
```

```
*       EA     = saturation vapour pressure [kPa]
*       T      = temperature [°C]
*       TK     = temperature [°K]
*       P      = atmospheric pressure at elevation z [kPa]
*       Z      = elevation above reference [m]
*       DELTA  = slope vapour pressure [kPa/°C]
*       GAMMA  = psychrometric constant [kPa/°C]
*       GAMMAK = corrected psychrometric constant [kPa/°C]
*       U2M    = measured windspeed at reference level [m/s]

      EAMIN = 0.6108 * EXP((17.27*TMIN)/(TMIN+237.3))
      EAMAX = 0.6108 * EXP((17.27*TMAX)/(TMAX+237.3))
      EA = (EAMIN+EAMAX)/2.0
      P = 101.3*((TK-0.0065*Z)/TK)**5.256

      DELTA = (4098*EA)/((T+237.3)**2)
      GAMMA = 1.6286E-3*(P/LABDA)
      GAMMAK = GAMMA*(1+0.347*U2M)

*----- Final calculation of radiation term


      RATERM = (DELTA/(DELTA+GAMMAK))*(RNET-G)


*-------- Final calculation of aerodynamic term

      AETERM = (GAMMA/(DELTA+GAMMAK))*(936.3/(T+274.3))*
     .             U2M*VPDM


*---------Final calculation of reference evapotranspiration


      TEMEXT = RATERM + AETERM
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C      2.b. Standardized new FAO-Temperature method      C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC


*    A. THE RADIATION TERM
**********************************************
*------ Calculation of net radiation------------
**********************************************

*-------Standardization of Relative Sunshine Fraction

       IF(RSF.LT.60.0) THEN
         RSMEAN = 0.45
       ELSEIF(RSF.GE.60.AND.RSF.LT.80) THEN
         RSMEAN = 0.70
       ELSEIF(RSF.GE.80) THEN
         RSMEAN = 0.90
       ENDIF


*------Calculation of extraterrestial radiation, Ra

       PHI = (LAT/360)*2*3.1416
       J = INT(30.42*MO-15.23)
       DR = 1 + 0.033 * COS(((2*3.1416)/365)*J)
       DEL = 0.4093*SIN(((2*3.1416)*(284+J))/365)
       OMEGA= ACOS(-TAN(PHI)*TAN(DEL))

       RA = ((24*60)/3.1416)*0.0820*DR*(OMEGA*SIN(PHI)*SIN(DEL)
     .      + COS(PHI)*COS(DEL)*SIN(OMEGA))

       RSHO = (ASN + (BSN*RSMEAN))*RA

       RNSHO = (1-ALPHA)*RSHO


C----- Parameterization of emissivity according to Idso and
C----- Jackson (1969)

      EPS = -0.02+0.261*EXP(-7.77E-4*T**2)

      RNLON = (0.9*RSMEAN+0.1)*EPS*SIGMA*
     . ((TKMAX**4+TKMIN**4)/2.0)

*------Final calculation of RNET, the net radiation------------

      RNET = RNSHO-RNLON

*------RNET in MJ/m2/day -----> RNET in mm/day----------------

      RNET = RNET/2.45
```

```
*----- Calculation of other parameters and variables relevant
*----- for radiation and aerodynamic term

      EAMIN = 0.6108 * EXP((17.27*TMIN)/(TMIN+237.3))
      EAMAX = 0.6108 * EXP((17.27*TMAX)/(TMAX+237.3))
      EA = (EAMIN+EAMAX)/2.0
      P = 101.3*((TK-0.0065*Z)/TK)**5.256

      DELTA = (4098*EA)/((T+237.3)**2)
      GAMMA = 1.6286E-3*(P/LABDA)

***********************************************************
*------1. Standardization of VPD and wind values
***********************************************************
*  The aerodynamic term is standardized for several general
*  levels of mean relative humidity. Relative humidity can
*  be classified as follows.
*  RHMEAN low          : <40 %  ,25 % used in model.
*  RHMEAN low-medium   : 40-55 %,48 % used in model.
*  RHMEAN medium-high  : 55-70 %,63 % used in model.
*  RHMEAN high         : >70 %  ,85 % used in model.
*  With these standardized values of RHMEAN the vapour pressure
*  at dewpoint can be calculated;


       IF(RH.LT.40.0) THEN
         RHMEAN = 25.0
       ELSEIF (RH.GE.40.0.AND.RH.LT.55.0) THEN
         RHMEAN = 48.0
       ELSEIF (RH.GE.55.0.AND.RH.LT.70.0) THEN
         RHMEAN = 63.0
       ELSEIF (RH.GT.70.0) THEN
         RHMEAN = 85.0
       ENDIF

       ED = EA*(RHMEAN/100.0)
       VPD = EA-ED

C  For the daytime wind (07.00-19.00 hours) values the following
C  classification is applied.
C  U2 low               : 0-2 m/s, 1.0 m/s used in model.
C  U2 moderate          : 2-5 m/s, 3.5 m/s used in model.
C  U2 high              : 5-8 m/s, 6.5 m/s used in model.
C  U2 very high         : >8 m/s ,10.0 m/s used in model.

       IF(U2M.LT.2.0) THEN
         U2 = 1.0
       ELSEIF (U2M.GE.2.0.AND.U2M.LT.5.0) THEN
         U2 = 3.5
       ELSEIF (U2M.GE.5.0.AND.U2M.LT.8.0) THEN
         U2 = 6.5
       ELSEIF (U2M.GT.8.0) THEN
         U2 = 10.0
       ENDIF

      GAMMAK = GAMMA*(1+0.347*U2)
```

```
*------ Final calculation of radiation term

      RATERM = (DELTA/(DELTA+GAMMAK))*(RNET-G)

*--------- Final calculation of aerodynamic term

      AETERM = (GAMMA/(DELTA+GAMMAK))*(936.3/(T+274.3))*
     .        U2*VPD


*---------Final calculation of reference evapotranspiration


      TEMSTA = RATERM + AETERM
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C  2.c Simplified new FAO-Temperature method                 C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

*------ Calculation of parameters and variables relevant
*------ for radiation and aerodynamic term

      EAMIN = 0.6108 * EXP((17.27*TMIN)/(TMIN+237.3))
      EAMAX = 0.6108 * EXP((17.27*TMAX)/(TMAX+237.3))
      EA = (EAMIN+EAMAX)/2.0
      P = 101.3*((TK-0.0065*Z)/TK)**5.256

      DELTA = (4098*EA)/((T+237.3)**2)
      GAMMA = 1.6286E-3*(P/LABDA)

**********************************************************
*-------1. Simplification of Vapour Pressure
**********************************************************


       ED = CORFAC * EXP((17.27*TMIN)/(TMIN+237.3))

       VPD = EA-ED

*    A. THE RADIATION TERM
**********************************************
*------ Calculation of net radiation------------
**********************************************
      IF(METHOD.EQ.1) THEN

*-------Calculation of RSHO as a function of maximum temperature

      IF(CCLASS.EQ.1.AND.TEMCLAS.EQ.1) THEN
        RSHO1 = 0.45*TMAX + 3.3
      ELSEIF(CCLASS.EQ.1.AND.TEMCLAS.EQ.2) THEN
        RSHO1 = 0.125*TMAX + 14.4
      ELSEIF(CCLASS.EQ.1.AND.TEMCLAS.EQ.3) THEN
        RSHO1 = 1.56*TMAX - 39.4
      ELSEIF(CCLASS.EQ.2.AND.TEMCLAS.EQ.1) THEN
        RSHO1 = 0.62*TMAX + 0.69
      ELSEIF(CCLASS.EQ.2.AND.TEMCLAS.EQ.2) THEN
        RSHO1 = 0.16*TMAX + 0.69
      ELSEIF(CCLASS.EQ.2.AND.TEMCLAS.EQ.3) THEN
        RSHO1 = 0.17*TMAX + 13.9
      ELSEIF(CCLASS.EQ.3.AND.TEMCLAS.EQ.1) THEN
        RSHO1 = 0.66*TMAX + 2.4
      ELSEIF(CCLASS.EQ.3.AND.TEMCLAS.EQ.2) THEN
        RSHO1 = 0.31*TMAX + 11.2
      ELSEIF(CCLASS.EQ.3.AND.TEMCLAS.EQ.3) THEN
        RSHO1 = 0.31*TMAX + 11.2
      ELSEIF(CCLASS.EQ.4.AND.TEMCLAS.EQ.1) THEN
        RSHO1 = 0.41*TMAX + 8.3
      ELSEIF(CCLASS.EQ.4.AND.TEMCLAS.EQ.2) THEN
        RSHO1 = 0.37*TMAX + 8.9
      ELSEIF(CCLASS.EQ.4.AND.TEMCLAS.EQ.3) THEN
        RSHO1 = 0.33*TMAX + 10.25
      ENDIF
```

```
*———Calculation of extraterrestial radiation, RA
*——— This parameter is needed to calculate RSF from RSHO

       PHI = (LAT/360)*2*3.1416
       J = INT(30.42*MO-15.23)
       DR = 1 + 0.033 * COS(((2*3.1416)/365)*J)
       DEL = 0.4093*SIN(((2*3.1416)*(284+J))/365)
       OMEGA= ACOS(-TAN(PHI)*TAN(DEL))

       RA = ((24*60)/3.1416)*0.0820*DR*(OMEGA*SIN(PHI)*SIN(DEL)
     .      + COS(PHI)*COS(DEL)*SIN(OMEGA))


      IF(CCLASS.GE.3) THEN
         A=0.25
         B=0.45
      ELSEIF(CCLASS.EQ.1.AND.T.GE.30.0) THEN
         A=0.29
         B=0.42
      ELSE
         A=0.18
         B=0.55
      ENDIF

      RSF = (RSHO1/(B*RA)) - A/B
      IF(RSF.GT.0.95) THEN
        RSF = 0.95
      ELSEIF(RSF.LT.0.10) THEN
        RSF = 0.10
      ENDIF
      RSHO = RSHO1

      GOTO 10
      ENDIF

**************************************************
* n/N is given as function of maximum temperature
* From n/N , RSHO is calculated
**************************************************
      IF(METHOD.EQ.2) THEN

      IF(CCLASS.EQ.1.AND.TEMCLAS.EQ.1) THEN
        RSF = (0.42*TMAX + 32.4)/100.0
      ELSEIF(CCLASS.EQ.1.AND.TEMCLAS.EQ.2) THEN
        RSF = (0.25*TMAX + 40.7)/100.0
      ELSEIF(CCLASS.EQ.1.AND.TEMCLAS.EQ.3) THEN
        RSF = (9.4*TMAX - 298.6)/100.0
      ELSEIF(CCLASS.EQ.2.AND.TEMCLAS.EQ.1) THEN
        RSF = (1.09*TMAX + 28.5)/100.0
      ELSEIF(CCLASS.EQ.2.AND.TEMCLAS.EQ.2) THEN
        RSF = (0.57*TMAX + 43.1)/100.0
      ELSEIF(CCLASS.EQ.2.AND.TEMCLAS.EQ.3) THEN
        RSF = (0.20*TMAX + 51.4)/100.0
      ELSEIF(CCLASS.EQ.3.AND.TEMCLAS.EQ.1) THEN
        RSF = (1.37*TMAX + 30.6)/100.0
```

```
      ELSEIF(CCLASS.EQ.3.AND.TEMCLAS.EQ.2) THEN
        RSF = (0.40*TMAX + 56.4)/100.0
      ELSEIF(CCLASS.EQ.3.AND.TEMCLAS.EQ.3) THEN
        RSF = (0.013*TMAX + 67.3)/100.0
      ELSEIF(CCLASS.EQ.4.AND.TEMCLAS.EQ.1) THEN
        RSF = (0.50*TMAX + 61.7)/100.0
      ELSEIF(CCLASS.EQ.4.AND.TEMCLAS.EQ.2) THEN
        RSF = (0.30*TMAX + 70.6)/100.0
      ELSEIF(CCLASS.EQ.4.AND.TEMCLAS.EQ.3) THEN
        RSF = (0.35*TMAX + 70.3)/100.0
      ENDIF

      IF(RSF.GT.0.95) THEN
        RSF = 0.95
      ELSEIF(RSF.LT.0.10) THEN
        RSF = 0.10
      ENDIF


      IF(CCLASS.GE.3) THEN
         A=0.25
         B=0.45
      ELSEIF(CCLASS.EQ.1.AND.T.GE.30.0) THEN
         A=0.29
         B=0.42
      ELSE
         A=0.18
         B=0.55
      ENDIF

*-------Calculation of extraterrestial radiation, RA
*------ This parameter is needed to calculate RSHO from RSF

       PHI = (LAT/360)*2*3.1416
       J = INT(30.42*MO-15.23)
       DR = 1 + 0.033 * COS(((2*3.1416)/365)*J)
       DEL = 0.4093*SIN(((2*3.1416)*(284+J))/365)
       OMEGA= ACOS(-TAN(PHI)*TAN(DEL))

       RA = ((24*60)/3.1416)*0.0820*DR*(OMEGA*SIN(PHI)*SIN(DEL)
     .      + COS(PHI)*COS(DEL)*SIN(OMEGA))

      RSHO2 = (A + (B*(RSF)))*RA
      RSHO=RSHO2

      ENDIF

****************************************************
* This option provides Global Incoming Radiation as
* a function of relative humidity
****************************************************
       IF(METHOD.EQ.3) THEN

       RELHUM = (ED/EA)*100.0

       IF(CCLASS.EQ.1) THEN
```

```
         RSHO3=-0.18*RELHUM+27.0
       ELSEIF(CCLASS.EQ.2) THEN
         RSHO3=-0.15*RELHUM+29.3
       ELSEIF(CCLASS.EQ.3) THEN
         RSHO3=-0.13*RELHUM+27.0
       ELSEIF(CCLASS.EQ.4) THEN
         RSHO3=-0.091*RELHUM+23.7
       ENDIF

****************************************************
* n/N is given as function of maximum temperature
* It is needed for longwave radiation
****************************************************

      IF(CCLASS.EQ.1.AND.TEMCLAS.EQ.1) THEN
        RSF = (0.42*TMAX + 32.4)/100.0
      ELSEIF(CCLASS.EQ.1.AND.TEMCLAS.EQ.2) THEN
        RSF = (0.25*TMAX + 40.7)/100.0
      ELSEIF(CCLASS.EQ.1.AND.TEMCLAS.EQ.3) THEN
        RSF = (9.4*TMAX - 298.6)/100.0
      ELSEIF(CCLASS.EQ.2.AND.TEMCLAS.EQ.1) THEN
        RSF = (1.09*TMAX + 28.5)/100.0
      ELSEIF(CCLASS.EQ.2.AND.TEMCLAS.EQ.2) THEN
        RSF = (0.57*TMAX + 43.1)/100.0
      ELSEIF(CCLASS.EQ.2.AND.TEMCLAS.EQ.3) THEN
        RSF = (0.20*TMAX + 51.4)/100.0
      ELSEIF(CCLASS.EQ.3.AND.TEMCLAS.EQ.1) THEN
        RSF = (1.37*TMAX + 30.6)/100.0
      ELSEIF(CCLASS.EQ.3.AND.TEMCLAS.EQ.2) THEN
        RSF = (0.40*TMAX + 56.4)/100.0
      ELSEIF(CCLASS.EQ.3.AND.TEMCLAS.EQ.3) THEN
        RSF = (0.013*TMAX + 67.3)/100.0
      ELSEIF(CCLASS.EQ.4.AND.TEMCLAS.EQ.1) THEN
        RSF = (0.50*TMAX + 61.7)/100.0
      ELSEIF(CCLASS.EQ.4.AND.TEMCLAS.EQ.2) THEN
        RSF = (0.30*TMAX + 70.6)/100.0
      ELSEIF(CCLASS.EQ.4.AND.TEMCLAS.EQ.3) THEN
        RSF = (0.35*TMAX + 70.3)/100.0
      ENDIF
       RSHO =RSHO3

       GOTO 10
      ENDIF


10    IF(RSHO.LT.0.0) THEN
        RSHO = 2.0
      ENDIF
      RNSHO = (1-ALPHA)*RSHO
```

```
C----- Parameterization of emissivity according to Idso and
C----- Jackson (1969)

      EPS = -0.02+0.261*EXP(-7.77E-4*T**2)

      RNLON = (0.9*(RSF)+0.1)*EPS*SIGMA*
     . ((TKMAX**4+TKMIN**4)/2.0)

*-------Final calculation of RNET, the net radiation-----------

      RNET = RNSHO-RNLON

*-------RNET in MJ/m2/day -----> RNET in mm/day----------------

      RNET = RNET/2.45


************************************************************
*------ Standardization of wind values                     *
************************************************************
C  For the daytime wind (07.00-19.00 hours) values the following
C  classification is applied.
C  U2 low               : 0-2 m/s, 1.0 m/s used in model.
C  U2 moderate          : 2-5 m/s, 3.5 m/s used in model.
C  U2 high              : 5-8 m/s, 6.5 m/s used in model.
C  U2 very high         : >8 m/s ,10.0 m/s used in model.

       IF(U2M.LT.2.0) THEN
         U2 = 1.0
       ELSEIF (U2M.GE.2.0.AND.U2M.LT.5.0) THEN
         U2 = 3.5
       ELSEIF (U2M.GE.5.0.AND.U2M.LT.8.0) THEN
         U2 = 6.5
       ELSEIF (U2M.GT.8.0) THEN
         U2 = 10.0
       ENDIF

      GAMMAK = GAMMA*(1+0.347*U2)

*----- Final calculation of radiation term


      RATERM = (DELTA/(DELTA+GAMMAK))*(RNET-G)

*-------- Final calculation of aerodynamic term

      AETERM = (GAMMA/(DELTA+GAMMAK))*(936.3/(T+274.3))*
     .              U2*VPD

      TEMSIM = RATERM + AETERM
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C   2.d   Hargreaves method                                     C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

*------Calculation of extraterrestial radiation, Ra

       PHI = (LAT/360)*2*3.1416
       J = INT(30.42*MO-15.23)
       DR = 1 + 0.033 * COS(((2*3.1416)/365)*J)
       DEL = 0.4093*SIN(((2*3.1416)*(284+J))/365)
       OMEGA= ACOS(-TAN(PHI)*TAN(DEL))

       RA = ((24*60)/3.1416)*0.0820*DR*(OMEGA*SIN(PHI)*SIN(DEL)
     .      + COS(PHI)*COS(DEL)*SIN(OMEGA))

*-----Hargreaves Formula

      TEMHAR = (0.0023*RA*(DELT)**0.5*(T+17.8))/2.45


****************************************************************
*                           OUTPUT                             *
****************************************************************

*----------Write various types of potential evapotranspiration to
*----------outputfile

      WRITE(41,'(1X,F7.4,1X,I2,9(1X,F5.2))') STATNR,MO,RADEXT,
     . RADSTA,RADSIM,RADRAD,RADPRI,TEMEXT,TEMSTA,TEMSIM,TEMHAR
      WRITE(*,*) 'N=',N
      GOTO 5

      END
```

APPENDIX 2.

AERO.FOR, a program for calculation of the aerodynamic term of Eq. (1) without the weigting factor $\gamma/\delta+\gamma^*$.
An example of input to this program is listed in AERO.DAT.

```
      PROGRAM AERO

C***********************************************************
C This program calculates the aerodynamic term (without W2)    *
C of the Combination Equation. The aerodynamic term is calcu- *
C lated for one relative humidity class with four windspeed    *
C options.                                                     *
C This relative humidity class has to be specified in the      *
C input file AERO.DAT                                          *
C The aerodynamic term is printed against temperature.         *
C                                                              *
C Author: Anne Verhoef                                         *
C Adress: Department of Hydrology,Soil Physics and Hydraulics *
C         Nieuwe Kanaal 11                                     *
C         6709 PA Wageningen                                   *
C         The Netherlands                                      *
C Date  : December 1990                                        *
C***********************************************************


      INTEGER RHCLAS,I,J,K,L,U2CLAS(4)
      REAL EA(20),T(20),ED(20),VPD(20),AETERM(4,20),U2(4),RHMEAN


******************************
*--- Initial section---
******************************
* Open input file
      OPEN(5,FILE='AERO.DAT',STATUS='OLD')

* Open output file
      OPEN(41,FILE='AERO.OUT',STATUS='UNKNOWN')
      READ(5,1) RHCLAS
      WRITE(41,5) RHCLAS
      WRITE(41,4)

1     FORMAT(I2)
2     FORMAT(F6.1)
3     FORMAT(F4.1)
4     FORMAT( '  T    1.0    3.5    6.5    10.0',/)
5     FORMAT(2X,'RHCLAS=',I2,/)


      DO 6 I=1,4
        READ(5,1) U2CLAS(I)
6     CONTINUE
```

```
      DO 10 J=1,20
        READ(5,3) T(J)
10    CONTINUE

      DO 50 K=1,4
        DO 45 L=1,20
*******************************

*******************************
*--- Initial calculations---
*******************************

*----- Calculation of variables relevant
*----- Aerodynamic term

*      EA     = saturation vapour pressure [kPa]
*      T      = temperature ['C]

      EA(L) = 0.6108 * EXP((17.27*T(L))/(T(L)+237.3))


C**********************************************************
C-------1. Standardization of VPD and wind values
C**********************************************************
C  The aerodynamic term is standardized for several general
C  levels of mean relative humidity. Relative humidity can
C  be classified as follows.
C  RHMEAN low          : <40 %  ,30 % used in model. class 1
C  RHMEAN low-medium   : 40-55 %,48 % used in model. class 2
C  RHMEAN medium-high  : 55-70 %,63 % used in model. class 3
C  RHMEAN high         : >70 %  ,85 % used in model. class 4
C  With these standardized values of RHMEAN the vapour pressure
C  at dewpoint can be calculated;

       IF(RHCLAS.EQ.1) THEN
         RHMEAN = 25.0
       ELSEIF (RHCLAS.EQ.2) THEN
         RHMEAN = 48.0
       ELSEIF (RHCLAS.EQ.3) THEN
         RHMEAN = 63.0
       ELSEIF (RHCLAS.EQ.4) THEN
         RHMEAN = 85.0
       ENDIF

       ED(L) = EA(L)*(RHMEAN/100.0)
       VPD(L) = EA(L)-ED(L)
```

```
***********************************************************
*------1. Standardization of wind values
***********************************************************

C  For the daytime wind (07.00-19.00 hours) values the following
C  classification is applied.
C  U2 low              : 0-2 m/s, 1.0 m/s used in model. class 1
C  U2 moderate         : 2-5 m/s, 3.5 m/s used in model. class 2
C  U2 high             : 5-8 m/s, 6.5 m/s used in model. class 3
C  U2 very high        : >8 m/s ,10.0 m/s used in model. class 4

       IF(U2CLAS(K).EQ.1) THEN
         U2(K) = 1.0
       ELSEIF (U2CLAS(K).EQ.2) THEN
         U2(K) = 3.5
       ELSEIF (U2CLAS(K).EQ.3) THEN
         U2(K) = 6.5
       ELSEIF (U2CLAS(K).EQ.4) THEN
         U2(K) = 10.0
       ENDIF

C------Calculation of the aerodynamic term (without weighting
C      factor)

      AETERM(K,L) = (936.3/(T(L)+274.3))*U2(K)*VPD(L)

45    CONTINUE
50    CONTINUE

* Write output to file

      DO 51 L=1,20
        WRITE(41,52)T(L),(AETERM(K,L),K=1,4)
51    CONTINUE
52    FORMAT(F4.0,4(1X,F6.2))
       STOP
       END
```

AERO.DAT, input file of program AERO.FOR.

```
3
1
2
3
4
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
22.0
24.0
26.0
28.0
30.0
32.0
34.0
36.0
38.0
40.0
```

APPENDIX 3.

DELGAM.FOR, a program which supplies the weighting factors $W1=\delta/\delta+\gamma^*$ and $W2=\gamma/\delta+\gamma^*$ of the proposed combination equation.
An example of the inputfile is also given.

```
      PROGRAM DELGAM

C*************************************************************
C This program calculates W1=DELTA/DELTA+GAMMAK and W2=GAMMA/ *
C DELTA+GAMMAK. W1 is the weighting factor for the effect of  *
C radiation on ETO, wheras W2 is a measure of the effect of   *
C the aerodynamic term on ETO.                                *
C                                                             *
C Author: Anne Verhoef                                        *
C Adress: Department of Hydrology,Soil Physics and Hydraulics *
C         Nieuwe Kanaal 11                                    *
C         6709 PA Wageningen                                  *
C         The Netherlands                                     *
C Date  : December 1990                                       *
C                                                             *
C*************************************************************


      INTEGER U2CLAS,I,J,K,L
      REAL EA(20),T(20),TK(20),P(11,20),Z(11),DELTA(20),
     . GAMMA(11,20),GAMMAK(11,20),U2,W1(11,20),W2(11,20),
     . LABDA

      DATA LABDA/2.45/



******************************
*--- Initial section---
******************************
* Open input file
      OPEN(5,FILE='DELGAM.DAT',STATUS='OLD')

* Open output file
      OPEN(41,FILE='DELGAM.OUT',STATUS='UNKNOWN')

      WRITE(41,4)

* Write heading in outputfile

1     FORMAT(I2)
2     FORMAT(F6.1)
3     FORMAT(F4.1)
4     FORMAT(/2X,' 2   4   6   8  10  12  14  16  18  20  22  24  26  28
     .  30  32  34  36  38  40',/)
```

```
* Read input file

      READ(5,1) U2CLAS

      DO 5 I=1,11
         READ(5,2) Z(I)
5     CONTINUE

      DO 10 J=1,20
        READ(5,3) T(J)
10    CONTINUE

      DO 50 K=1,11
        DO 45 L=1,20


*******************************
*--- Initial calculations---
*******************************

*------ Calculation of variables relevant
*------ for DELTA, GAMMA and GAMMAK

*       EA     = saturation vapour pressure [kPa]
*       T      = temperature ['C]
*       TK     = temperature [K]
*       P      = atmospheric pressure at elevation z [kPa]
*       Z      = elevation above reference [m]
*       DELTA  = slope vapour pressure [kPa/'c]
*       GAMMA  = psychrometric constant [kPa/'C]
*       GAMMAK = corrected psychrometric constant [kPa/'C]
*       U2     = windspeed at reference level [m/s]

      EA(L) = 0.6108 * EXP((17.27*T(L))/(T(L)+237.3))
      TK(L) = T(L) + 273.16
      P(K,L) = 101.3*((TK(L)-0.0065*Z(K))/TK(L))**5.256


      DELTA(L) = (4098*EA(L))/((T(L)+237.3)**2)
      GAMMA(K,L) = 1.6286E-3*(P(K,L)/LABDA)

***********************************************************
*-------1. Standardization of wind values
***********************************************************

C  For the daytime wind (07.00-19.00 hours) values the following
C  classification is applied.
C  U2 low            : 0-2 m/s, 1.0 m/s used in model. class 1
C  U2 moderate       : 2-5 m/s, 3.5 m/s used in model. class 2
C  U2 high           : 5-8 m/s, 6.5 m/s used in model. class 3
C  U2 very high      : >8 m/s ,10.0 m/s used in model. class 4

       IF(U2CLAS.EQ.1) THEN
         U2 = 1.0
       ELSEIF (U2CLAS.EQ.2) THEN
         U2 = 3.5
```

```
        ELSEIF (U2CLAS.EQ.3) THEN
          U2 = 6.5
        ELSEIF (U2CLAS.EQ.4) THEN
          U2 = 10.0
        ENDIF

      GAMMAK(K,L) = GAMMA(K,L)*(1+0.347*U2)

* Calculation of weighting factors

      W1(K,L) = (DELTA(L)/(DELTA(L)+GAMMAK(K,L)))
      W2(K,L) = (GAMMA(K,L)/(DELTA(L)+GAMMAK(K,L)))

45    CONTINUE

* Writing of W1 or W2 to output file

      WRITE(41,51)(W1(K,L),L=1,20)
50    CONTINUE
51    FORMAT(20(1X,F3.2))
      STOP
      END
```

DELGAM.DAT, input to program DELGAM.FOR

```
1
0.0
250.0
500.0
750.0
1000.0
1500.0
2000.0
2500.0
3000.0
3500.0
4000.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
22.0
24.0
26.0
28.0
30.0
32.0
34.0
36.0
38.0
40.0
```

APPENDIX 4.

The following program give the stationnumbers and accessory meteorological parameters for 4 precipitation classes (see Table 2.2), whereas the air temperature difference is less than 15.

This outputfile can be used for calculation of potential evaporation by the program PEVAP.FOR. The programs which consider air temperature differences of 15-20 and 20-40 C have a similar structure.

```
**************************************************************
* This program reads data from the FAO data-files PAR01.DAT, *
* PAR03.DAT,PAR04.DAT,PAR05.DAT,PAR07.DAT,PAR08.DAT, PAR09.  *
* DAT, STATIONS.DAT and STAT.DAT.                            *
* It lists the variables from these files,plus derived para- *
* meters, per stationnumber. Output is given only for those  *
* months, which have Tmax-Tmin values < 15 degrees.          *
**************************************************************

      PROGRAM READLT15

      INTEGER J,RAIN(12),HEIGHT
      REAL COUNT1,COUNT3,COUNT4,COUNT5,COUNT7,COUNT8,COUNT9,
     . COUNTS
      REAL LONG,LAT
      REAL TEMP(12),TMAX(12),TMIN(12),SUN(12),VP(12),DELTT(12)
      REAL EAMIN(12),EAMAX(12),EA(12),VPD(12)
      REAL RH(12),U2(12),GLOB(12)


C     Opening of input- and outputfiles.

      OPEN(21,FILE='PAR01.DAT',STATUS='OLD')
      OPEN(23,FILE='PAR03.DAT',STATUS='OLD')
      OPEN(24,FILE='PAR04.DAT',STATUS='OLD')
      OPEN(25,FILE='PAR05.DAT',STATUS='OLD')
      OPEN(27,FILE='PAR07.DAT',STATUS='OLD')
      OPEN(28,FILE='PAR08.DAT',STATUS='OLD')
      OPEN(29,FILE='PAR09.DAT',STATUS='OLD')
      OPEN(30,FILE='STAT.DAT',STATUS='OLD')
      OPEN(40,FILE='HUM15.OUT',STATUS='NEW')
      OPEN(41,FILE='SUBH15.OUT',STATUS='NEW')
      OPEN(42,FILE='SEMA15.OUT',STATUS='NEW')
      OPEN(43,FILE='ARI15.OUT',STATUS='NEW')

C     Reading of rainfall, maximum temperature,
C     minimum temperature, actual vapour pressure, wind-
C     speed, relative sunshine fraction, global radiation,
C     stationnumber, latitude, longitude and height

10      READ(21,*) COUNT1,(RAIN(J),J=1,12)

        READ(23,*) COUNT3,(TMAX(J),J=1,12)
```

```
      READ(24,*) COUNT4,(TMIN(J),J=1,12)

      READ(25,*) COUNT5,(VP(J),J=1,12)

      READ(27,*) COUNT7,(U2(J),J=1,12)

      READ(28,*) COUNT8,(SUN(J),J=1,12)

      READ(29,*) COUNT9,(GLOB(J),J=1,12)

      READ(30,*) COUNTS,LAT,LONG,HEIGHT


C     Calculation of average temperature, Tmax-Tmin,
C     saturated vapour pressure, vapour pressure deficit,
C     slope saturated VP-curve, and relative humidity

      DO 20 J=1,12

       TEMP(J)=(TMAX(J)+TMIN(J))/2.0
       DELTT(J)=TMAX(J)-TMIN(J)
       EAMIN(J)=0.6108*EXP((17.27*TMIN(J))/(TMIN(J)+237.3))
       EAMAX(J)=0.6108*EXP((17.27*TMAX(J))/(TMAX(J)+237.3))
       EA(J)=(EAMIN(J)+EAMAX(J))/2.0
       VPD(J)=EA(J)-VP(J)
       RH(J)=(VP(J)/EA(J))*100.0


     IF(VPD(J).GT.0.0) THEN
         IF(DELTT(J).LT.15.0.AND.RAIN(J).GT.150) THEN

         WRITE(40,'(1X,F7.4,1X,F7.2,1X,F7.2,1X,I4,1X,I2,1X,
     .   F6.2,1X,I4,1X,F5.1,1X,F5.1,1X,
     .   F5.1,1X,F5.1,1X,F4.2,1X,F6.2,1X,F4.0,1X,F4.1,1X,
     .   F4.1)')
     .   COUNT1,LAT,LONG,HEIGHT,J,TEMP(J),RAIN(J),TMAX(J),
     .   TMIN(J),DELTT(J),SUN(J),VP(J),VPD(J),RH(J),
     .   GLOB(J),U2(J)
         ENDIF


     IF(DELTT(J).LT.15.0.AND.RAIN(J).GT.70.AND.RAIN(J).LE.150)THEN

         WRITE(41,'(1X,F7.4,1X,F7.2,1X,F7.2,1X,I4,1X,I2,1X,
     .   F6.2,1X,I4,1X,F5.1,1X,F5.1,1X,
     .   F5.1,1X,F5.1,1X,F4.2,1X,F6.2,1X,F4.0,1X,F4.1,1X,
     .   F4.1)')
     .   COUNT1,LAT,LONG,HEIGHT,J,TEMP(J),RAIN(J),TMAX(J),
     .   TMIN(J),DELTT(J),SUN(J),VP(J),VPD(J),RH(J),
     .   GLOB(J),U2(J)
         ENDIF

     IF(DELTT(J).LT.15.0.AND.RAIN(J).GT.20.AND.RAIN(J).LE.70)THEN

         WRITE(42,'(1X,F7.4,1X,F7.2,1X,F7.2,1X,I4,1X,I2,1X,
     .   F6.2,1X,I4,1X,F5.1,1X,F5.1,1X,
```

```
     .    F5.1,1X,F5.1,1X,F4.2,1X,F6.2,1X,F4.0,1X,F4.1,1X,
     .    F4.1)')
     .    COUNT1,LAT,LONG,HEIGHT,J,TEMP(J),RAIN(J),TMAX(J),
     .    TMIN(J),DELTT(J),SUN(J),VP(J),VPD(J),RH(J),
     .    GLOB(J),U2(J)
          ENDIF

      IF(DELTT(J).LT.15.0.AND.RAIN(J).LE.20) THEN

          WRITE(43,'(1X,F7.4,1X,F7.2,1X,F7.2,1X,I4,1X,I2,1X,
     .    F6.2,1X,I4,1X,F5.1,1X,F5.1,1X,
     .    F5.1,1X,F5.1,1X,F4.2,1X,F6.2,1X,F4.0,1X,F4.1,1X,
     .    F4.1)')
     .    COUNT1,LAT,LONG,HEIGHT,J,TEMP(J),RAIN(J),TMAX(J),
     .    TMIN(J),DELTT(J),SUN(J),VP(J),VPD(J),RH(J),
     .    GLOB(J),U2(J)
          ENDIF
        ENDIF
20     CONTINUE
       GOTO 10

      CLOSE(40)
      CLOSE(41)
      CLOSE(42)
      CLOSE(43)


      STOP
      END
```

APPENDIX 5.

CORSEE.FOR, a program for calculation of the correlation between several Temperature and Radiation Methods and the Combination Equation (Eq. (1) of this report). The program also supplies standard errors of estimate.

```
*****************************************************************
* This program is based on the subroutine PEARSN.FOR of         *
*'Numerical Recipes'.  It calculates the linear correlation     *
* coefficient between the so-called Extended new FAO-Radiation  *
* method and methods derived from this equation or other methods*
* (like the Original FAO-Radiation method, Priestley-Taylor     *
* method, or the Hargreaves method.                             *
* An extension was made by incorporating the so-called Standard *
* Error of Estimate (SEE), which was based on the concept of    *
* Jensen et al.                                                 *
*                                                               *
*                                                               *
* Author: Anne Verhoef                                          *
*                                                               *
*         Department of Hydrology, Soil Physics and Hydraulics  *
*         Agricultural University, Wageningen                   *
*         The Netherlands                                       *
*                                                               *
* Date  : February 1991                                         *
*                                                               *
*****************************************************************

      PROGRAM CORSEE
      PARAMETER (TINY=1.E-20)

      INTEGER MO(1000),METHOD
      REAL STNR(1000),REXT(1000),RSTA(1000),RSIM(1000)
      REAL RRAD(1000),RPRI(1000),TEXT(1000),TSTA(1000)
      REAL TSIM(1000),THAR(1000),X(1000),Y(1000),ERROR(1000)
      REAL SUMERR,SEE
      CHARACTER INPUT*25,OUTPUT*25


*------- Initial Section
*------- Interactive input

        WRITE(*,'(A$)') ' GIVE NAME INPUTFILE:'
        READ(*,'(A)') INPUT
        WRITE(*,'(A$)') ' GIVE NAME OUTPUTFILE:'
        READ(*,'(A)') OUTPUT

        WRITE(*,'(A$)') ' N:'
        READ(*,*) N
```

```
      OPEN(41,FILE=INPUT,STATUS='OLD')
      OPEN(42,FILE=OUTPUT,STATUS='NEW')

      DO 5  J=1,N

*------- Reading of potential evapotranspiration originating
*------- from several methods

       READ(41,*) STNR(J),MO(J),REXT(J),RSTA(J),RSIM(J),
     .            RRAD(J),RPRI(J),TEXT(J),TSTA(J),TSIM(J),
     .            THAR(J)

        X(J)=REXT(J)

5     CONTINUE
*------- Determination of correlation coefficient between
*------- the extended radiation method and other selected methods

      METHOD = 0
6     CONTINUE
      SUMERR=0.0
      METHOD = METHOD + 1
      DO 7 J=1,N

        IF (METHOD.EQ.1) THEN
          Y(J)=RSTA(J)
        ELSEIF (METHOD.EQ.2) THEN
          Y(J)=RSIM(J)
        ELSEIF (METHOD.EQ.3) THEN
          Y(J)=RRAD(J)
        ELSEIF (METHOD.EQ.4) THEN
          Y(J)=RPRI(J)
        ELSEIF (METHOD.EQ.5) THEN
          Y(J)=TEXT(J)
        ELSEIF (METHOD.EQ.6) THEN
          Y(J)=TSTA(J)
        ELSEIF (METHOD.EQ.7) THEN
          Y(J)=TSIM(J)
        ELSEIF (METHOD.EQ.8) THEN
          Y(J)=THAR(J)
        ENDIF

*------- Intermediate calculations for SEE

        ERROR(J)=(X(J)-Y(J))**2
        SUMERR=SUMERR+ERROR(J)

7     CONTINUE
      AX=0.
      AY=0.
      DO 11 J=1,N
        AX=AX+X(J)
        AY=AY+Y(J)
11    CONTINUE
      AX=AX/N
      AY=AY/N
```

```
      SXX=0.
      SYY=0.
      SXY=0.
      DO 12 J=1,N
        XT=X(J)-AX
        YT=Y(J)-AY
        SXX=SXX+XT**2
        SYY=SYY+YT**2
        SXY=SXY+XT*YT
12    CONTINUE

*------ Final calculation of r

      R=SXY/SQRT(SXX*SYY)
      Z=0.5*ALOG(((1.+R)+TINY)/((1.-R)+TINY))
      DF=N-2
      T=R*SQRT(DF/(((1.-R)+TINY)*((1.+R)+TINY)))
C      PROB=BETAI(0.5*DF,0.5,DF/(DF+T**2))
      PROB=ERFCC(ABS(Z*SQRT(N-1.))/1.4142136)

*------ Final calculation of SEE

      SEE = (SUMERR/(N-1))**0.5
      WRITE(42,'(I2,1X,F4.2,F5.2)') METHOD,R,SEE
      IF(METHOD.EQ.8) GOTO 20
      GOTO 6
20    CONTINUE

      STOP
      END

      FUNCTION BETAI(A,B,X)
      IF(X.LT.0..OR.X.GT.1.)PAUSE 'bad argument X in BETAI'
      IF(X.EQ.0..OR.X.EQ.1.)THEN
        BT=0.
      ELSE
        BT=EXP(GAMMLN(A+B)-GAMMLN(A)-GAMMLN(B)
     *      +A*ALOG(X)+B*ALOG(1.-X))
      ENDIF
      IF(X.LT.(A+1.)/(A+B+2.))THEN
        BETAI=BT*BETACF(A,B,X)/A
        RETURN
      ELSE
        BETAI=1.-BT*BETACF(B,A,1.-X)/B
        RETURN
      ENDIF
      END
```