PRELIMINARY REVIEW OF REVISED FAO RADIATION AND TEMPERATURE METHODS

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Abbreviations

PET = Potential evapotranspiration [mm/d]
PM = Penman-Monteith
RADEX = 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:

\[
ET_o = \frac{\delta}{\delta + \gamma^*} \cdot \frac{1}{\lambda} \cdot \frac{936}{\eta} \cdot \frac{R_n - G}{\eta} \cdot \frac{U_2 \cdot (e_a - e_d)}{(T_{\text{avg}} + 276)}
\]

where:

- \(ET_o\): 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
- \(T_{\text{avg}}\): Average temperature [°C]
- \(U_2\): Windspeed measured at 2 m [m/s]
- \((e_a - e_d)\): Vapour pressure deficit [kPa]
- \(\delta\): Slope of vapour pressure curve [kPa/°C]
- \(\lambda\): Latent heat of vaporization [MJ/kg]
- \(\gamma\): Adiabatic psychrometric constant [kPa/°C]
- \(\gamma^*\): 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.*

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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

\[
R_{ns} = (1-\alpha) \times R_a
\]  

with

\( R_{ns} \) : Net shortwave radiation \([\text{MJ/m}^2\cdot\text{d}]\)
\( \alpha \) : Canopy reflection coefficient
\( = 0.23 \) overall average for grass
\( R_a \) : Incoming solar radiation \([\text{MJ/m}^2\cdot\text{d}]\)

The incoming solar radiation is not measured but given by

\[
R_a = (a_{sn} + b_{sn} \frac{n}{N}) \times R_a
\]  

\( R_a \) : Incoming solar radiation \([\text{MJ/m}^2\cdot\text{d}]\)
\( a_{sn} \) : 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.
\( \frac{n}{N} \) : Relative sunshine fraction
\( n \) : Bright sunshine hours per day \([\text{hr}]\)
\( N \) : Total daylength \([\text{hr}]\)

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

\[
R_{nl} = (0.9 \frac{n}{N} - 0.1) \times (0.34-0.139/{e_d}) \times 0.5 \times (T_{\text{max}}^{-4} + T_{\text{min}}^{-4})
\]  

\( R_{nl} \) : Net longwave radiation \([\text{MJ/m}^2\cdot\text{d}]\)
\( e_d \) : Dew point vapour pressure \([\text{kPa}]\)
\( T_{\text{max}} \) : Maximum temperature \([\text{K}]\)
\( T_{\text{min}} \) : Minimum temperature \([\text{K}]\)
\( \sigma \) : Stefan Boltzman constant \([\text{MJ/m}^2\cdot\text{K}^4\cdot\text{d}]\)
\( = 4.903 \times 10^{-8} \)

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

\[
\epsilon = -0.02 + 0.261 \exp(-7.77 \times 10^{-4} \times T_{\text{avg}}^2)
\]  

\( T_{\text{avg}} \) : Average daily temperature \([\degree \text{C}]\)

The extraterrestrial radiation, \( R_a \), can be calculated from the following formulas as given in Smith, 1991.

\[
R_a = 37.586 \times D_e \times (\Omega \times \sin(\phi) \times \sin(\delta) + \cos(\phi) \times \cos(\delta) \times \sin(\Omega))
\]  

\( R_a \) : Extraterrestrial radiation \([\text{MJ/m}^2\cdot\text{d}]\)
\( D_e \) : Daily effective sun constant \([\text{MJ/m}^2\cdot\text{hr}]\)
\( \Omega \) : Right ascension \([\text{rad}]\)
\( \phi \) : Co-latitude \([\text{rad}]\)
\( \delta \) : Declination \([\text{rad}]\)

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Where:

\[
\Phi = \left(\frac{\theta}{360}\right) \times 2 \times 3.1416 \\
J = 30.42 \times MO - 15.23 \\
D_r = 1 + 0.033 \times \cos\left(\frac{2\pi}{365} \times J\right) \\
\delta = 0.4093 \times \sin\left(\frac{2\pi}{365} \times (284 + J)\right) \\
\Omega = \arccos\left(\cos(-\tan(\Phi) \times \tan(\delta))\right)
\]

(7) (8) (9) (10) (11)

In which:

- \(D_r\): Relative distance from earth to sun [rad]
- \(\Omega\): Sunset hour angle [rad]
- \(\Phi\): Latitude in radians [rad]
- \(\theta\): Latitude in degrees [deg]
- \(\delta\): 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 \(T_{\text{min}}\) and \(T_{\text{max}}\).

\[
e_a(T_{\text{avg}}) = \frac{e_a(T_{\text{min}}) + e_a(T_{\text{max}})}{2}
\]

(12)

Where dewpoint data are available:

\[
e_d = 0.6108 \times \exp\left(\frac{17.27 \times T_{\text{min}}}{T_{\text{min}} + 237.3}\right)
\]

Otherwise \(e_d\) is obtained as:

\[
e_d = e_a \times \left(\frac{\text{RH}_{\text{avg}}}{100}\right)
\]

(13)

Where

- \(T_{\text{avg}}\): Average temperature, \((T_{\text{max}} - T_{\text{min}})/2\) [°C]
- \(\text{RH}_{\text{avg}}\): 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):

$$e_d = C_f \times \exp(\frac{17.27 \times T_{\text{min}}}{T_{\text{min}}+237.3})$$  \hspace{1cm} (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 $\delta/\delta+y^*$ and $\gamma/\delta+y^*$ in front of the radiation and aerodynamic terms of Eq. (1) consist of $\gamma$, $\gamma^*$ and $\delta$. These variables are defined in the following way.

The adiabatic psychrometric constant, $\gamma$:

$$\gamma = 1.63 \times 10^{-3} \times \frac{P}{\lambda}$$ \hspace{1cm} (15)$$

$P$ : Atmospheric pressure [kPa]
$\lambda$ : Latent heat [MJ/kg]

The modified psychrometric constant, $\gamma^*$:

$$\gamma^* = \gamma (1 + 0.347 \times U_2)$$ \hspace{1cm} (16)$$

The slope of the vapour pressure curve, $\delta$:

$$\delta = \frac{4098 \times e_a(T_{\text{avg}})}{(T_{\text{avg}}+237.3)^2}$$ \hspace{1cm} (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 addressed 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&V-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 \( R_s \), \( n/N \), \( T_{\text{max}} \) and \( T_{\text{min}} \), 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 \( T_{\text{max}} \) and \( T_{\text{min}} \), \( R_s \) 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 \( ET_0 \) and several meteorological parameters is given by:

\[
ET_0 = \frac{(c \times (W \times R_s))}{2.45} \tag{18}
\]

Where:

- \( ET_0 \): 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 \( \text{ET}_0 \) 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

\[
\delta \frac{\text{ET}_0}{\delta + \gamma} = (\alpha \frac{(R_n - G)}{2.45})
\]

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:

\[ \text{ET}_0 = \frac{(c [p(0.46T_{\text{avg}} + 8)])}{2.45} \]  \hspace{1cm} (20)

where:
- \( \text{ET}_0 \): 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-terrestrial radiation (in this case) as extra input. It is defined by the following equation:

\[ \text{ET}_0 = \frac{(0.0023 R_a \times (T_{\text{max}} - T_{\text{min}}) \times *(T_{\text{avg}} + 17.8))}{2.45} \]  \hspace{1cm} (21)

Where:
- \( R_a \): The extraterrestrial 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 \( T_{\text{max}} - T_{\text{min}} \) 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 $T_{\text{max}} - T_{\text{min}}$, 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 $T_{\text{max}} - T_{\text{min}}$ values as a possible parameter to improve aerodynamic term estimates (see A.)

5. Propose a generalized form for the Temperature Method, using $T_{\text{max}}$ and $T_{\text{min}}$ 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/cm².d]. These data were calculated from the extraterrestrial 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:

<table>
<thead>
<tr>
<th>Climate</th>
<th>$a_{sn}$</th>
<th>$b_{sn}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arid, semi-arid</td>
<td>0.25</td>
<td>0.45</td>
</tr>
<tr>
<td>Tropical humid</td>
<td>0.29</td>
<td>0.42</td>
</tr>
<tr>
<td>Other</td>
<td>0.18</td>
<td>0.55</td>
</tr>
</tbody>
</table>

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 parameter 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/cm².d was transformed in MJ/m².d by multiplication with 0.041868. Actual vapour pressure in mbar was changed to actual vapour pressure in kPa through 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.

2.1. 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 \( W_1 \) and \( W_2 \) (\( 5/(5+7^*) \) and \( 7/(5+7^*) \), 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 ($T_{av}$), for relative humidity class 1 and 4 windspeed options.
Table 2.1. Weighting factor $W_l = 6/(6+\gamma)$ as a function of the average air temperature ($T_{\text{avg}}$) and altitude of the meteorological station. Windspeed is 3.5 m/s.

| Air Temperature (°C) | Weight | 2  | 4  | 6  | 8  | 10 | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 26 | 28 | 30 | 32 | 34 | 36 | 38 |
|---------------------|--------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 0                   | 0.36   | 0.39 | 0.42 | 0.45 | 0.48 | 0.50 | 0.53 | 0.56 | 0.59 | 0.61 | 0.64 | 0.66 | 0.69 | 0.71 | 0.73 | 0.75 | 0.77 | 0.78 | 0.80 |
| 250                 | 0.36   | 0.39 | 0.42 | 0.45 | 0.48 | 0.51 | 0.54 | 0.57 | 0.60 | 0.62 | 0.65 | 0.67 | 0.69 | 0.71 | 0.73 | 0.75 | 0.77 | 0.79 | 0.80 |
| 500                 | 0.37   | 0.40 | 0.43 | 0.46 | 0.49 | 0.52 | 0.55 | 0.58 | 0.60 | 0.63 | 0.65 | 0.68 | 0.70 | 0.72 | 0.74 | 0.76 | 0.78 | 0.79 | 0.81 |
| 750                 | 0.38   | 0.41 | 0.44 | 0.47 | 0.50 | 0.53 | 0.56 | 0.58 | 0.61 | 0.64 | 0.66 | 0.68 | 0.70 | 0.73 | 0.75 | 0.77 | 0.78 | 0.80 | 0.81 |
| 1000                | 0.39   | 0.42 | 0.45 | 0.48 | 0.51 | 0.54 | 0.56 | 0.59 | 0.62 | 0.64 | 0.67 | 0.69 | 0.71 | 0.73 | 0.75 | 0.77 | 0.79 | 0.80 | 0.82 |
| 1500                | 0.40   | 0.43 | 0.46 | 0.49 | 0.52 | 0.55 | 0.58 | 0.61 | 0.63 | 0.66 | 0.68 | 0.70 | 0.72 | 0.74 | 0.76 | 0.78 | 0.79 | 0.81 | 0.82 |
| 2000                | 0.42   | 0.45 | 0.48 | 0.51 | 0.54 | 0.57 | 0.59 | 0.62 | 0.65 | 0.67 | 0.69 | 0.71 | 0.73 | 0.75 | 0.77 | 0.79 | 0.80 | 0.82 | 0.83 |
| 2500                | 0.43   | 0.46 | 0.49 | 0.52 | 0.55 | 0.58 | 0.60 | 0.63 | 0.66 | 0.68 | 0.70 | 0.72 | 0.74 | 0.76 | 0.78 | 0.79 | 0.81 | 0.83 | 0.84 |
| 3000                | 0.45   | 0.48 | 0.51 | 0.54 | 0.57 | 0.60 | 0.62 | 0.65 | 0.67 | 0.69 | 0.71 | 0.73 | 0.75 | 0.77 | 0.79 | 0.81 | 0.83 | 0.84 | 0.85 |
| 3500                | 0.47   | 0.50 | 0.53 | 0.56 | 0.58 | 0.61 | 0.64 | 0.66 | 0.69 | 0.71 | 0.73 | 0.75 | 0.77 | 0.79 | 0.80 | 0.82 | 0.83 | 0.84 | 0.85 |
| 4000                | 0.48   | 0.51 | 0.54 | 0.57 | 0.60 | 0.63 | 0.65 | 0.68 | 0.70 | 0.72 | 0.74 | 0.76 | 0.78 | 0.80 | 0.81 | 0.83 | 0.84 | 0.85 | 0.86 |

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.

<table>
<thead>
<tr>
<th>Rainfall</th>
<th>Mean daily temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humid</td>
<td>&gt; 150 mm/month</td>
</tr>
<tr>
<td>Subhumid</td>
<td>70–150 mm/month</td>
</tr>
<tr>
<td>Semi-arid</td>
<td>20–70 mm/month</td>
</tr>
<tr>
<td>Arid</td>
<td>0–20 mm/month</td>
</tr>
</tbody>
</table>

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 throughout 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.](image)

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 \( T_{\text{max}} - T_{\text{min}} \) 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 \( T_{\text{max}} - T_{\text{min}} \) values, and thus will not have identical relationships between this temperature difference and other meteorological parameters.

Fig. 2.3. Variation of maximum (\( T_{\text{max}} \)) and minimum (\( T_{\text{min}} \)) temperature, and the difference (\( T_{\text{max}} - T_{\text{min}} \)) 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 \( T_{\text{max}} - T_{\text{min}} \) 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 \((T_{\text{max}} - T_{\text{min}})\) 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.
Mean temperature > 10 and < 20 °C
Monthly rainfall > 150 mm

Fig. 2.8. Actual vapour pressure ($e_a$) 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 ($R_g$) 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 \((T_{\text{max}}-T_{\text{min}})\). 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 \((T_{\text{max}}-T_{\text{min}})\) 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 \((T_{\text{max}}-T_{\text{min}})\) has to be considered as a sort of rough humidity indicator, like in the Hargreaves method.

This dependence of relative humidity on \((T_{\text{max}}-T_{\text{min}})\) 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 \((T_{\text{max}}-T_{\text{min}})\) 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.

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

On the basis of this division 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, whereas 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 $> 15^\circ$, 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 ($T_{\text{min}}$) 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 exponential 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 (\( \delta \)) to, for example, minimum temperature, \( T_{\text{max}}-T_{\text{min}} \), rainfall amount etc. This because knowledge of \( \delta \) leads immediately to the actual vapour pressure, as \( \delta \) 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, $\delta$. 

Monthly temperature fluctuation ($T_{MAX} - T_{MIN}$): 20-40 °C
Monthly rainfall < 20 mm: Arid

Monthly temperature fluctuation ($T_{MAX} - T_{MIN}$): 15-20 °C
Monthly rainfall < 20 mm: Arid
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 $C_f = f(T_{\text{min}})$

Furthermore, because actual vapour pressure is only one of the various parameters determining potential evapotranspiration, 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, \( T_{\text{max}} - T_{\text{min}} < 15 \, ^\circ \text{C} \)

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

\[
e_d = 0.673 \times \exp (0.0626 \times T_{\text{min}}) \tag{22}
\]

Where:

- \( e_d \) : Average monthly actual vapour pressure [kPa].
- \( T_{\text{min}} \) : Average monthly minimum temperature [°C].

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min. Value</th>
<th>Max. Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{max}} ) °C</td>
<td>-4</td>
<td>38</td>
</tr>
<tr>
<td>( T_{\text{min}} ) °C</td>
<td>-13</td>
<td>28</td>
</tr>
<tr>
<td>RH %</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>( R_s ) Mj/m(^2).d</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>n/N %</td>
<td>10</td>
<td>75</td>
</tr>
</tbody>
</table>

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, \( T_{\text{max}} - T_{\text{min}} = 15-20 \, ^\circ \text{C} \)

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).

\[
e_d = 0.892 \times \exp (0.056 \times T_{\text{min}}) \tag{23}
\]

Common features of the stations belonging to this class are given in Table 2.4.
Table 2.4. Parameter ranges of the H1520 climate.

<table>
<thead>
<tr>
<th></th>
<th>$T_{\text{max}}$</th>
<th>$T_{\text{min}}$</th>
<th>RH</th>
<th>$R_s$</th>
<th>n/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>°C</td>
<td>%</td>
<td>Mj/m$^2$.d</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Min. Value</td>
<td>17</td>
<td>2</td>
<td>50</td>
<td>13</td>
<td>20</td>
</tr>
<tr>
<td>Max. Value</td>
<td>37</td>
<td>20</td>
<td>95</td>
<td>24</td>
<td>80</td>
</tr>
</tbody>
</table>

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 $T_{\text{min}}$-$e_d$ relationship for the H1520 climate.

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

<table>
<thead>
<tr>
<th>Station</th>
<th>Country</th>
<th>Lat.</th>
<th>Long.</th>
<th>Height</th>
<th>Mo</th>
<th>Tmin</th>
<th>VP</th>
<th>Cf1</th>
<th>Cf2</th>
</tr>
</thead>
<tbody>
<tr>
<td>63.02900 ETH</td>
<td>14.53</td>
<td>38.49</td>
<td>2022</td>
<td>7</td>
<td>5.70</td>
<td>1.39</td>
<td>.93</td>
<td>1.01</td>
<td></td>
</tr>
<tr>
<td>63.02900 ETH</td>
<td>14.53</td>
<td>38.49</td>
<td>2022</td>
<td>8</td>
<td>6.60</td>
<td>1.40</td>
<td>.88</td>
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<td></td>
</tr>
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<td>12.57</td>
<td>36.04</td>
<td>803</td>
<td>6</td>
<td>19.00</td>
<td>2.54</td>
<td>.67</td>
<td>.83</td>
<td></td>
</tr>
<tr>
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<td>12.20</td>
<td>37.14</td>
<td>2150</td>
<td>7</td>
<td>8.40</td>
<td>1.51</td>
<td>.84</td>
<td>.94</td>
<td></td>
</tr>
<tr>
<td>63.31700 ETH</td>
<td>12.20</td>
<td>37.14</td>
<td>2150</td>
<td>8</td>
<td>8.70</td>
<td>1.52</td>
<td>.83</td>
<td>.93</td>
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<tr>
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<td>38.02</td>
<td>2410</td>
<td>6</td>
<td>9.00</td>
<td>1.39</td>
<td>.74</td>
<td>.84</td>
<td></td>
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<td>36.55</td>
<td>2180</td>
<td>6</td>
<td>9.50</td>
<td>1.42</td>
<td>.73</td>
<td>.83</td>
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<tr>
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<td>11.13</td>
<td>40.03</td>
<td>1660</td>
<td>7</td>
<td>10.70</td>
<td>1.46</td>
<td>.69</td>
<td>.80</td>
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<tr>
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<td>40.03</td>
<td>1660</td>
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<td>39.41</td>
<td>2200</td>
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<td>1.41</td>
<td>.56</td>
<td>.66</td>
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<tr>
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<td>2200</td>
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<td>15.60</td>
<td>2.13</td>
<td>.73</td>
<td>.89</td>
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<td>1600</td>
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<td>.78</td>
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<td>1300</td>
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<td>.63</td>
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<td>37.23</td>
<td>2320</td>
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<td>8.50</td>
<td>1.25</td>
<td>.69</td>
<td>.78</td>
<td></td>
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<td>1200</td>
<td>10</td>
<td>13.00</td>
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<td>.76</td>
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<td>2040</td>
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<tr>
<td>63.43700 ETH</td>
<td>8.08</td>
<td>39.35</td>
<td>2600</td>
<td>8</td>
<td>8.10</td>
<td>1.54</td>
<td>.87</td>
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<td>530</td>
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<td>.97</td>
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<td>34.24</td>
<td>530</td>
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<td>16.20</td>
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<td>530</td>
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<td>36.11</td>
<td>1950</td>
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<td>.85</td>
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</tr>
<tr>
<td>63.45700 ETH</td>
<td>7.16</td>
<td>36.11</td>
<td>1950</td>
<td>5</td>
<td>11.50</td>
<td>1.70</td>
<td>.77</td>
<td>.89</td>
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</tr>
<tr>
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<td>35.15</td>
<td>1200</td>
<td>5</td>
<td>13.50</td>
<td>1.95</td>
<td>.77</td>
<td>.92</td>
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<td>35.15</td>
<td>1200</td>
<td>7</td>
<td>13.40</td>
<td>2.14</td>
<td>.85</td>
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</tr>
<tr>
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<td>36.17</td>
<td>1725</td>
<td>4</td>
<td>12.70</td>
<td>1.73</td>
<td>.72</td>
<td>.85</td>
<td></td>
</tr>
<tr>
<td>63.48100 ETH</td>
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<td>2540</td>
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<td>5.10</td>
<td>1.18</td>
<td>.82</td>
<td>.89</td>
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</tr>
<tr>
<td>63.48100 ETH</td>
<td>6.58</td>
<td>39.11</td>
<td>2540</td>
<td>8</td>
<td>5.10</td>
<td>1.24</td>
<td>.86</td>
<td>.93</td>
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</tr>
<tr>
<td>63.48800 ETH</td>
<td>6.46</td>
<td>38.23</td>
<td>1835</td>
<td>4</td>
<td>11.10</td>
<td>1.67</td>
<td>.77</td>
<td>.90</td>
<td></td>
</tr>
<tr>
<td>63.49800 ETH</td>
<td>6.35</td>
<td>38.25</td>
<td>1860</td>
<td>6</td>
<td>10.20</td>
<td>1.61</td>
<td>.79</td>
<td>.91</td>
<td></td>
</tr>
<tr>
<td>63.49800 ETH</td>
<td>6.35</td>
<td>38.25</td>
<td>1860</td>
<td>5</td>
<td>8.90</td>
<td>1.60</td>
<td>.86</td>
<td>.97</td>
<td></td>
</tr>
<tr>
<td>63.49800 ETH</td>
<td>6.35</td>
<td>38.25</td>
<td>1860</td>
<td>9</td>
<td>9.40</td>
<td>1.59</td>
<td>.82</td>
<td>.94</td>
<td></td>
</tr>
<tr>
<td>63.49800 ETH</td>
<td>6.35</td>
<td>38.25</td>
<td>1860</td>
<td>10</td>
<td>8.30</td>
<td>1.38</td>
<td>.77</td>
<td>.87</td>
<td></td>
</tr>
<tr>
<td>63.50500 ETH</td>
<td>6.25</td>
<td>38.18</td>
<td>1670</td>
<td>4</td>
<td>13.50</td>
<td>1.88</td>
<td>.74</td>
<td>.88</td>
<td></td>
</tr>
</tbody>
</table>
2.4.3. Humid, $T_{\text{max}} - T_{\text{min}}$: 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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$T_{\text{max}}$</th>
<th>$T_{\text{min}}$</th>
<th>RH</th>
<th>$R_s$</th>
<th>n/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>°C</td>
<td>%</td>
<td>Mj/m².d</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Min. Value</td>
<td>35.4</td>
<td>14.8</td>
<td>48</td>
<td>16</td>
<td>36</td>
</tr>
<tr>
<td>Max. Value</td>
<td>37.4</td>
<td>17.3</td>
<td>62</td>
<td>19</td>
<td>53</td>
</tr>
</tbody>
</table>

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

2.4.4. Subhumid, $T_{\text{max}} - T_{\text{min}}$: < 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 $T_{\text{min}}$ and $e_d$ is as follows.

$$e_d = 0.624 \times \exp (0.0632 \times T_{\text{min}})$$  \hspace{1cm} (24)

Possible parameter ranges for this climate are listed in Table 2.8.
Table 2.8. Parameter ranges of the SH15 climate.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( T_{\max} ) (^\circC)</th>
<th>( T_{\min} ) (^\circC)</th>
<th>RH</th>
<th>( R_s ) Mj/m(^2).d</th>
<th>n/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Value</td>
<td>-5</td>
<td>-14</td>
<td>48</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Max. Value</td>
<td>42</td>
<td>31</td>
<td>62</td>
<td>26</td>
<td>80</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Country</th>
<th>Specifics</th>
<th>Coefficient ( C_f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>Height &gt; 500</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Coastal area, Plains</td>
<td>0.65</td>
</tr>
<tr>
<td>Luxembourg</td>
<td></td>
<td>0.76</td>
</tr>
<tr>
<td>France</td>
<td>Coast Channel</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>Coast Mediterranean</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>River area</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>Les Landes/Gascogne</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>Massif Central</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>Dauphine</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Corsica</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>0.65</td>
</tr>
<tr>
<td>Spain</td>
<td>Coastal town North</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>Coastal region North</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>Coastal town West</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>Coastal region West</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>Coastal town East</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>Gulf of Valencia, Mallorca</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>Menorca</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>Ibiza</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>Interior</td>
<td>0.62</td>
</tr>
<tr>
<td>Portugal</td>
<td>Coastal area West</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>Interior &gt; 500 m</td>
<td>0.77</td>
</tr>
<tr>
<td>Capeverdian</td>
<td></td>
<td>0.54</td>
</tr>
<tr>
<td>Islands</td>
<td>Coastal town</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>Coastal area</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>Coastal area &gt; 500</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>River area</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>Interior</td>
<td>0.64</td>
</tr>
</tbody>
</table>
2.4.5. Subhumid, $T_{\text{max}} - T_{\text{min}}$: 15–20 °C

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

$$e_d = 0.805 \times \exp (0.051 \times T_{\text{min}})$$ (25)

Ranges of relevant parameters are given in Table 2.10.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min. Value</th>
<th>Max. Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{max}}$</td>
<td>12°C</td>
<td>38°C</td>
</tr>
<tr>
<td>$T_{\text{min}}$</td>
<td>-5°C</td>
<td>25°C</td>
</tr>
<tr>
<td>RH</td>
<td>30%</td>
<td>100%</td>
</tr>
<tr>
<td>$R_s$</td>
<td>10 Mj/m².d</td>
<td>26 Mj/m².d</td>
</tr>
<tr>
<td>n/N</td>
<td>30%</td>
<td>90%</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Country</th>
<th>Height</th>
<th>Extra</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>individual</td>
</tr>
<tr>
<td>Turkey</td>
<td>2000</td>
<td></td>
<td>0.82</td>
</tr>
<tr>
<td>Afghanistan</td>
<td>1200</td>
<td>Island</td>
<td>0.79</td>
</tr>
<tr>
<td>SRI Lanka</td>
<td>1880</td>
<td></td>
<td>1.02</td>
</tr>
<tr>
<td>Burma</td>
<td>1078</td>
<td></td>
<td>0.61</td>
</tr>
<tr>
<td>Thailand</td>
<td>395</td>
<td></td>
<td>0.84</td>
</tr>
<tr>
<td>Sudan</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>month 7-12</td>
<td>0.89</td>
</tr>
<tr>
<td>Uganda</td>
<td></td>
<td>month 0-6</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>month 7-12</td>
<td>0.88</td>
</tr>
<tr>
<td>Zaire</td>
<td></td>
<td>near lake</td>
<td>1.04</td>
</tr>
<tr>
<td>Burundi</td>
<td></td>
<td></td>
<td>0.88</td>
</tr>
<tr>
<td>Centrafrica</td>
<td></td>
<td></td>
<td>0.80</td>
</tr>
<tr>
<td>Liberia</td>
<td></td>
<td></td>
<td>0.80</td>
</tr>
<tr>
<td>Angola</td>
<td></td>
<td>Coastal area</td>
<td>1.16</td>
</tr>
<tr>
<td></td>
<td>&gt;1000</td>
<td>rain&gt;100</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>&gt;1000</td>
<td>rain&lt;100</td>
<td>0.52</td>
</tr>
<tr>
<td>Mozambique</td>
<td></td>
<td>Coastal</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Interior</td>
<td>0.84</td>
</tr>
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<td>Zambia</td>
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<td></td>
<td></td>
<td>0.57</td>
</tr>
<tr>
<td>South-Africa</td>
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<td>River area</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Interior</td>
<td>0.74</td>
</tr>
<tr>
<td>Mexico</td>
<td></td>
<td>s.coast</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>&gt;2000</td>
<td>e.coast</td>
<td>0.82</td>
</tr>
<tr>
<td>Haiti</td>
<td></td>
<td></td>
<td>1.00</td>
</tr>
<tr>
<td>Guatemala</td>
<td>&gt;1000</td>
<td></td>
<td>0.88</td>
</tr>
<tr>
<td>Honduras</td>
<td>&lt;100</td>
<td>n.coast</td>
<td>1.18</td>
</tr>
<tr>
<td>Ecuador</td>
<td>&gt;2500</td>
<td></td>
<td>0.77</td>
</tr>
<tr>
<td>Chili</td>
<td>&lt;1000</td>
<td>month 1-6</td>
<td>0.77</td>
</tr>
<tr>
<td>Paraguay</td>
<td></td>
<td>month 7-12</td>
<td>0.99</td>
</tr>
<tr>
<td>Uruguay</td>
<td></td>
<td></td>
<td>0.76</td>
</tr>
<tr>
<td>Sumatra</td>
<td>&gt;500</td>
<td></td>
<td>0.90</td>
</tr>
<tr>
<td>Borneo</td>
<td></td>
<td></td>
<td>0.96</td>
</tr>
</tbody>
</table>
2.4.6. Subhumid, $T_{\text{max}} - T_{\text{min}}$: 20–40 °C.

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

$$e_d = 1.07 \times \exp(0.040 T_{\text{min}})$$

Eq. (26)

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

Table 2.12. Parameter ranges of the SH2040 climate.

<table>
<thead>
<tr>
<th></th>
<th>$T_{\text{max}}$</th>
<th>$T_{\text{min}}$</th>
<th>RH</th>
<th>$R_s$</th>
<th>n/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min.</td>
<td>°C</td>
<td>°C</td>
<td>%</td>
<td>Mj/m².d</td>
<td>%</td>
</tr>
<tr>
<td>Value</td>
<td>19</td>
<td>-3</td>
<td>50</td>
<td>11</td>
<td>44</td>
</tr>
<tr>
<td>Max.</td>
<td>41</td>
<td>18</td>
<td>100</td>
<td>24</td>
<td>83</td>
</tr>
</tbody>
</table>

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

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

$$e_d = 0.612 \times \exp(0.059 T_{\text{min}})$$

Eq. (27)

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

Table 2.13. Parameter ranges of the SA15 climate.

<table>
<thead>
<tr>
<th></th>
<th>$T_{\text{max}}$</th>
<th>$T_{\text{min}}$</th>
<th>RH</th>
<th>$R_s$</th>
<th>n/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min.</td>
<td>°C</td>
<td>°C</td>
<td>%</td>
<td>Mj/m².d</td>
<td>%</td>
</tr>
<tr>
<td>Value</td>
<td>-8</td>
<td>-18</td>
<td>22</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Max.</td>
<td>42</td>
<td>30</td>
<td>100</td>
<td>27</td>
<td>95</td>
</tr>
</tbody>
</table>

Because of the large amount of stations comprising in this class no table of coefficients is supplied.
2.4.8. Semi-arid, $T_{\text{max}} - T_{\text{min}} : 15-20 \, ^{\circ}\text{C}$

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

$$e_d = 0.682 \times \exp (0.054\times T_{\text{min}})$$  \hspace{1cm} (28)

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

Table 2.14. Parameter ranges of the SA1520 climate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min. Value</th>
<th>Max. Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{max}}$</td>
<td>-8°C</td>
<td>42°C</td>
</tr>
<tr>
<td>$T_{\text{min}}$</td>
<td>-22°C</td>
<td>28°C</td>
</tr>
<tr>
<td>RH</td>
<td>20%</td>
<td>80%</td>
</tr>
<tr>
<td>$R_s$</td>
<td>5 Mj/m².d</td>
<td>30 Mj/m².d</td>
</tr>
<tr>
<td>n/N</td>
<td>30%</td>
<td>95%</td>
</tr>
</tbody>
</table>

2.4.9. Semi-arid, $T_{\text{max}} - T_{\text{min}} : 20-40 \, ^{\circ}\text{C}$

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

$$e_d = 0.734 \times \exp (0.065\times T_{\text{min}})$$  \hspace{1cm} (29)

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

Table 2.15. Parameter ranges of the SA2040 climate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min. Value</th>
<th>Max. Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{max}}$</td>
<td>-11°C</td>
<td>42°C</td>
</tr>
<tr>
<td>$T_{\text{min}}$</td>
<td>-8°C</td>
<td>18°C</td>
</tr>
<tr>
<td>RH</td>
<td>38%</td>
<td>88%</td>
</tr>
<tr>
<td>$R_s$</td>
<td>13 Mj/m².d</td>
<td>27 Mj/m².d</td>
</tr>
<tr>
<td>n/N</td>
<td>38%</td>
<td>98%</td>
</tr>
</tbody>
</table>
2.4.10. Arid, \( T_{\text{max}} - T_{\text{min}} : < 15^\circ\text{C} \)

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

\[
ed = 0.521 \times \exp (0.062 \times T_{\text{min}}) \quad (30)
\]

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

Table 2.16. Parameter ranges of the A15 climate.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min. Value</th>
<th>Max. Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{max}} )</td>
<td>-20°C</td>
<td>43°C</td>
</tr>
<tr>
<td>( T_{\text{min}} )</td>
<td>-35°C</td>
<td>32°C</td>
</tr>
<tr>
<td>RH</td>
<td>20%</td>
<td>95%</td>
</tr>
<tr>
<td>( R_s )</td>
<td>2 Mj/m².d</td>
<td>30 Mj/m².d</td>
</tr>
<tr>
<td>( n/N )</td>
<td>20%</td>
<td>95%</td>
</tr>
</tbody>
</table>

2.4.11. Arid, \( T_{\text{max}} - T_{\text{min}} : 15-20 \ ^\circ\text{C} \)

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

\[
ed = 0.621 \times \exp (0.041 \times T_{\text{min}}) \quad (31)
\]

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

Table 2.17. Parameter ranges of the A1520 climate.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min. Value</th>
<th>Max. Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{max}} )</td>
<td>-25°C</td>
<td>45°C</td>
</tr>
<tr>
<td>( T_{\text{min}} )</td>
<td>-39°C</td>
<td>30°C</td>
</tr>
<tr>
<td>RH</td>
<td>10%</td>
<td>80%</td>
</tr>
<tr>
<td>( R_s )</td>
<td>3 Mj/m².d</td>
<td>32 Mj/m².d</td>
</tr>
<tr>
<td>( n/N )</td>
<td>50%</td>
<td>95%</td>
</tr>
</tbody>
</table>
2.4.12. Arid, $T_{\text{max}} - T_{\text{min}} : 20-40 \, ^\circ\text{C}$

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

$$e_d = 0.588 \times \exp (0.046 \times T_{\text{min}})$$

(32)

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

Table 2.18. Parameter ranges of the A2040 climate

<table>
<thead>
<tr>
<th></th>
<th>$T_{\text{max}}$</th>
<th>$T_{\text{min}}$</th>
<th>RH</th>
<th>$R_s$</th>
<th>n/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Value</td>
<td>-5</td>
<td>-20</td>
<td>20</td>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td>Max. Value</td>
<td>45</td>
<td>40</td>
<td>75</td>
<td>32</td>
<td>95</td>
</tr>
</tbody>
</table>

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 \( T_{\text{max}} - T_{\text{min}} \).

In Chapter 1 however, it was found that the correlation between \( T_{\text{max}} - T_{\text{min}} \) and \( \eta/N \) 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 \( T_{\text{max}} \) as the independent variable as this requires one computation less (if we assume \( T_{\text{avg}} = (T_{\text{max}} + T_{\text{min}})/2 \)).

Fig. 2.13 shows that the correlation is promising, but that at a certain maximum temperature, incoming global radiation still could vary considerably.
A relationship between relative sunshine fraction and maximum temperature also exists, but it appears to be more scattered. (See Fig. 2.14).

Monthly temperature fluctuation (TMAX-TMIN) ≤ 15 °C
Monthly rainfall > 20 mm and ≤ 70 mm: semi-arid

Fig. 2.14. Relative sunshine fraction (n/N) as a function of maximum air temperature (Tmax) 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 meteorological 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 mountainous area.
Variation of monthly incoming global radiation with maximum temperature, Zaragoza, Spain.

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:

$$R_s(i,j) = a(i) \times T_{max}(i,j) + b(i)$$  \hspace{1cm} (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 $\delta T_{MAX1}$ and $\delta T_{MAX2}$.

It appeared that both $a$ and $b$ revealed an exponential dependence on $\delta T_{MAX}$. A graphical representation of this statement is given in Fig. 2.16, which shows the $a$ and $b$ factors as a function of $\delta T_{MAX1}$ for several sites in Europe.

The shapes of the curves can be described by the functions:

$$a = -0.811 \times \ln(\delta T_{MAX1}) + 3.29$$  \hspace{1cm} (34)
$$b = 17.79 \times \ln(\delta T_{MAX1}) - 52.26$$  \hspace{1cm} (35)
Fig. 2.16 Parameters $a$ and $b$ in the relationship $R_{d} = a \cdot T_{\text{Max}} + b$ as a function of $\delta T_{\text{Max}}$. 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 $\delta T_{\text{Max}}$ 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 SAl5-climate.

Fig. 2.19. Global incoming radiation \((R_a)\) as a function of relative humidity \((RH)\) for stations of the SAl5-climate.
The relationship between relative humidity and relative sunshine fraction seems good enough to use as a substitute 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 ($R_\text{g}$) 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

<table>
<thead>
<tr>
<th>Climate Class</th>
<th>Temperature difference Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humid</td>
<td>&lt; 15 °C</td>
</tr>
<tr>
<td>Subhumid</td>
<td>15-20 °C</td>
</tr>
<tr>
<td>Semi-arid</td>
<td>20-40 °C</td>
</tr>
<tr>
<td>Arid</td>
<td></td>
</tr>
</tbody>
</table>

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 README15.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

<table>
<thead>
<tr>
<th>RADEXT</th>
<th>RADSTA</th>
<th>RADSIM</th>
<th>RADORI</th>
<th>RADPRI</th>
<th>TEMEXT</th>
<th>TEMSTA</th>
<th>TEMSIM</th>
<th>TEMHAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitude</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Month</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{\text{max}}$</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>$T_{\text{min}}$</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>$T_{\text{max}}-T_{\text{min}}$</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n/N$</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>E</td>
<td>E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_a$</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td>f($T_{\text{max}}$)</td>
</tr>
<tr>
<td>$R_a$</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e_d$</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>f($T_{\text{min}}$)</td>
</tr>
<tr>
<td>$e_a-e_d$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RH</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$U_2$</td>
<td>*</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>*</td>
<td>E</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>$C_f$</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* 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**

<table>
<thead>
<tr>
<th>Climate</th>
<th>Equation</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vapour pressure = f(T_{min}) [kPa]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humid</td>
<td>( e_d = C_f \times \exp\left(\frac{T_{min} \times 17.27}{T_{min} + 237.3}\right) )</td>
<td>( C_f = 0.61 )</td>
</tr>
<tr>
<td>Subhumid</td>
<td>&quot;</td>
<td>( C_f = 0.61 )</td>
</tr>
<tr>
<td>Semi-arid</td>
<td>&quot;</td>
<td>( C_f = 0.55 )</td>
</tr>
<tr>
<td>Arid</td>
<td>&quot;</td>
<td>( C_f = -0.016 \times T_{min} + 0.66 )</td>
</tr>
</tbody>
</table>

**Vapour pressure = f(e_a(T) - \gamma(T_{max} - T_{min}))**

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

*(Smith, personal communication)*

**Incoming Global Radiation = f(T_{max}) [MJ/m^2.d] Method 1**

<table>
<thead>
<tr>
<th>Climate</th>
<th>Equation</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humid</td>
<td>( R_a = 0.45 \times T_{max} + 3.3 )</td>
<td></td>
</tr>
<tr>
<td>( \delta T &lt; 15 \ ^\circ C )</td>
<td>( R_a = 0.62 \times T_{max} + 0.7 )</td>
<td></td>
</tr>
<tr>
<td>( \delta T = 15-20 \ ^\circ C )</td>
<td>( R_a = 0.13 \times T_{max} + 14.4 )</td>
<td></td>
</tr>
<tr>
<td>( \delta T = 20-40 \ ^\circ C )</td>
<td>( R_a = 1.56 \times T_{max} - 39.4 )</td>
<td></td>
</tr>
<tr>
<td>Subhumid</td>
<td>( R_a = 0.62 \times T_{max} + 0.7 )</td>
<td></td>
</tr>
<tr>
<td>( \delta T &lt; 15 \ ^\circ C )</td>
<td>( R_a = 0.13 \times T_{max} + 14.4 )</td>
<td></td>
</tr>
<tr>
<td>( \delta T = 15-20 \ ^\circ C )</td>
<td>( R_a = 0.17 \times T_{max} + 13.9 )</td>
<td></td>
</tr>
<tr>
<td>( \delta T = 20-40 \ ^\circ C )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-arid</td>
<td>( R_a = 0.66 \times T_{max} + 2.4 )</td>
<td></td>
</tr>
<tr>
<td>( \delta T &lt; 15 \ ^\circ C )</td>
<td>( R_a = 0.31 \times T_{max} + 11.1 )</td>
<td></td>
</tr>
<tr>
<td>( \delta T = 15-20 \ ^\circ C )</td>
<td>( R_a = 0.31 \times T_{max} + 11.1 )</td>
<td></td>
</tr>
<tr>
<td>( \delta T = 20-40 \ ^\circ C )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arid</td>
<td>( R_a = 0.41 \times T_{max} + 8.3 )</td>
<td></td>
</tr>
<tr>
<td>( \delta T &lt; 15 \ ^\circ C )</td>
<td>( R_a = 0.37 \times T_{max} + 8.9 )</td>
<td></td>
</tr>
<tr>
<td>( \delta T = 15-20 \ ^\circ C )</td>
<td>( R_a = 0.28 \times T_{max} + 11.6 )</td>
<td></td>
</tr>
<tr>
<td>( \delta T = 20-40 \ ^\circ C )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( n/N = R_a/(b*R_a) - a/b \)
Where \( R_a \) is extraterrestrial 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 \( = f(T_{\text{max}}) \)

**Method 2**

<table>
<thead>
<tr>
<th>Humid</th>
<th>( \delta T &lt; 15 ) °C</th>
<th>( n/N = 0.42 * T_{\text{max}} + 32.4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \delta T = 15-20 ) °C</td>
<td>( n/N = 0.25 * T_{\text{max}} + 40.7 )</td>
</tr>
<tr>
<td></td>
<td>( \delta T = 20-40 ) °C</td>
<td>( n/N = 9.40 * T_{\text{max}} - 298.6 )</td>
</tr>
<tr>
<td>Subhumid</td>
<td>( \delta T &lt; 15 ) °C</td>
<td>( n/N = 1.09 * T_{\text{max}} + 28.5 )</td>
</tr>
<tr>
<td></td>
<td>( \delta T = 15-20 ) °C</td>
<td>( n/N = 0.57 * T_{\text{max}} + 43.1 )</td>
</tr>
<tr>
<td></td>
<td>( \delta T = 20-40 ) °C</td>
<td>( n/N = 0.20 * T_{\text{max}} + 51.4 )</td>
</tr>
<tr>
<td>Semi-arid</td>
<td>( \delta T &lt; 15 ) °C</td>
<td>( n/N = 1.37 * T_{\text{max}} + 30.6 )</td>
</tr>
<tr>
<td></td>
<td>( \delta T = 15-20 ) °C</td>
<td>( n/N = 0.40 * T_{\text{max}} + 56.4 )</td>
</tr>
<tr>
<td></td>
<td>( \delta T = 20-40 ) °C</td>
<td>( n/N = 0.01 * T_{\text{max}} + 67.3 )</td>
</tr>
<tr>
<td>Arid</td>
<td>( \delta T &lt; 15 ) °C</td>
<td>( n/N = 0.50 * T_{\text{max}} + 61.7 )</td>
</tr>
<tr>
<td></td>
<td>( \delta T = 15-20 ) °C</td>
<td>( n/N = 0.30 * T_{\text{max}} + 70.6 )</td>
</tr>
<tr>
<td></td>
<td>( \delta T = 20-40 ) °C</td>
<td>( n/N = 0.35 * T_{\text{max}} + 70.3 )</td>
</tr>
</tbody>
</table>

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

### Incoming Global Radiation \( = f(RH) \) [MJ/m².d] **Method 3**

<table>
<thead>
<tr>
<th>Humid</th>
<th>( R_s = -0.18 * RH + 27.0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subhumid</td>
<td>( R_s = -0.15 * RH + 29.3 )</td>
</tr>
<tr>
<td>Semi-arid</td>
<td>( R_s = -0.13 * RH + 27.0 )</td>
</tr>
<tr>
<td>Arid</td>
<td>( R_s = -0.12 * RH + 25.6 )</td>
</tr>
</tbody>
</table>

\( n/N = f(T_{\text{max}}) \)

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. 3.3a 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.
Humid, $T_{max} - T_{min} < 15^\circ C$
Incoming Solar Radiation = $f(T_{max})$, $n/N = f(R_{SHO})$, $VP = f(T_{min})$
Correction factor in VP-equation = 0.61

Subhumid, $T_{max} - T_{min} < 15^\circ C$
Incoming Solar Radiation = $f(T_{max})$, $n/N = f(R_{SHO})$, $VP = f(T_{min})$
Correction factor in VP-equation = 0.61

Semi-arid, $T_{max} - T_{min} = 15-20^\circ C$
Incoming Solar Radiation = $f(T_{max})$, $n/N = f(R_{SHO})$, $VP = f(T_{min})$
Correction factor in VP-equation = 0.53

Arid, $T_{max} - T_{min} = 20-40^\circ C$
Incoming Solar Radiation = $f(T_{max})$, $n/N = f(R_{SHO})$, $VP = f(T_{min})$
Correction factor in VP-equation = $-0.016+0.010 +0.66$

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.

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

(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 $e_d = C_d f(T_{min})$. For the simplified Temperature Method $R_s = f(T_{max})$ and $n/N = f(R_s)$: method 1.

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

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 evapotranspiration, 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.

\[ W = \frac{\delta}{(\delta+\gamma)} \text{ and } 1-W \text{ in stead of } \frac{\delta}{(\delta+\gamma')}, \text{ and } \frac{\gamma}{(\delta+\gamma')} \]. 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 estimations 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. (D)).

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 $R_s$, $T_{avg}$ 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, whereas 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.

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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 is indicated by Table 3.5.

Table 3.5. Correlation coefficients and standard errors of estimate of simplified Temperature method versus the extended Radiation Method. 

<table>
<thead>
<tr>
<th>Climate</th>
<th>Method</th>
<th>r</th>
<th>SEE</th>
<th>r</th>
<th>SEE</th>
<th>r</th>
<th>SEE</th>
<th>r</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humid</td>
<td>TEMSIM</td>
<td>0.96</td>
<td>0.41</td>
<td>0.95</td>
<td>0.34</td>
<td>0.92</td>
<td>0.66</td>
<td>0.92</td>
<td>0.77</td>
</tr>
<tr>
<td>Subhumid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-arid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 preferred 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.

![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.](image)

Table 3.6. Correlation coefficients and standard errors of estimate of simplified Temperature method versus the extended Radiation Method.

<table>
<thead>
<tr>
<th>Climate</th>
<th>Humid</th>
<th>Subhumid</th>
<th>Semi-arid</th>
<th>Arid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
<td>r</td>
<td>SEE</td>
<td>r</td>
<td>SEE</td>
</tr>
<tr>
<td>TEMSIM</td>
<td>0.82</td>
<td>0.97</td>
<td>0.84</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>0.81</td>
<td>1.02</td>
<td>0.87</td>
<td>0.89</td>
</tr>
</tbody>
</table>
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;

\[ e_d = \frac{(a \times e_a(T_{ave}) - \gamma(T_{max} - T_{min}) + b)}{10.0} \quad (36) \]

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 \( e_a \), \( \gamma \) and \( T_{max} - T_{min} \). Climate Classes are H15 and A2040, respectively.
4. CONCLUSIONS

* It is not justified to correlate $T_{\text{max}} - T_{\text{min}}$, divided into small intervals, with certain meteorological parameters. Temperature difference $(T_{\text{max}} - T_{\text{min}})$ 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 $C_r$ 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 higher 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, extraterrestrial 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 extraterrestrial radiation, \( T_{\text{max}} - T_{\text{min}} \) and \( T_{\text{avg}} \) 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 extraterrestrial radiation is an indicator of global incoming radiation, whereas \( T_{\text{max}} - T_{\text{min}} \) is related to relative humidity.
Literature


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
INTEGER MO,N,Z,J,CCLASS
INTEGER TEMCLAS,METHOD
REAL RSRO, RNSHO, RSF, RA, EPS, ED, RNLO, 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/O.0/, ALPHA/0.23/, as/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
A. THE RADIATION TERM

Calculation of net radiation

1. SHORTWAVE RADIATION

\[ R_{NSHO} = (1 - \text{ALPHA}) \times R_{SHO} \]

2. LONGWAVE RADIATION

\[ R_{NLON} = (0.9 \times (\text{RSF}/100) + 0.1) \times \text{EPS} \times \sigma \times \frac{(T_{\text{MAX}}^4 + T_{\text{MIN}}^4)}{2.0} \]

Calculation of \( R_{NET} \), the net radiation

\[ R_{NET} = R_{NSHO} - R_{NLON} \]

Note: \( R_{NET} \) in MJ/m²/d is converted to mm/d by dividing by 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
A. THE RADIATION TERM

Calculation of net radiation

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

\[
R_{NSHO} = (1-\alpha)R_{SHO}
\]

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

\[
\epsilon = -0.02 + 0.261 \exp(-7.77 \times 10^{-4} T^2)
\]

\[
R_{NLON} = 0.9 \left(\frac{R_{SF}/100 + 0.1}{\epsilon \sigma (T_{KMAX}^4 + T_{KMIN}^4)/2.0}\right)
\]

--- Final calculation of R\text{NET}, the net radiation

\[
R_{NET} = R_{NSHO} - R_{NLON}
\]

--- R\text{NET} in MJ/m²/d \rightarrow R\text{NET} in mm/d

\[
R_{NET} = \frac{R_{NET}}{2.45}
\]

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

\[
E_{AMIN} = 0.6108 \exp\left(\frac{17.27 T_{MIN}}{(T_{MIN}+237.3)}\right)
\]

\[
E_{AMAX} = 0.6108 \exp\left(\frac{17.27 T_{MAX}}{(T_{MAX}+237.3)}\right)
\]

\[
E_A = \frac{E_{AMIN} + E_{AMAX}}{2.0}
\]

\[
P = 101.3 \left(\frac{(T+0.0065Z)/T}{100}\right)^5.256
\]

\[
\Delta = \frac{4098 \times E_A}{(T+237.3)^2}
\]

\[
\Gamma = 1.6286 \times 10^{-3} \left(P/L\alpha D\right)
\]

--- 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.

* RH\text{MEAN} low : <40 %, 25 % used in model.
* RH\text{MEAN} low-medium : 40–55 %, 48 % used in model.
* RH\text{MEAN} medium-high : 55–70 %, 63 % used in model.
* RH\text{MEAN} high : >70 %, 85 % used in model.

With these standardized values of RH\text{MEAN} 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
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)

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

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

RADSTA = RATERM + AETERM
* A. THE RADIATION TERM

*******Calculation of net radiation*******

*—Incoming solar radiation is measured

\[
RNSHO = (1-\alpha) \times RSHO
\]

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

\[
\text{EPS} = -0.02 + 0.261 \times \exp(-7.77 \times 10^{-4} \times T^2)
\]

\[
RNLON = (0.9 \times (RSF/100) + 0.1) \times \text{EPS} \times \sigma \times \left( \frac{T_{\text{KMAX}}^4 + T_{\text{KMIN}}^4}{2} \right)
\]

*—Final calculation of \text{RNET}, the net radiation

\[
\text{RNET} = RNSHO - RNLON
\]

—RNET in MJ/m²/d ———> RNET in mm/d ————

\[
\text{RNET} = \text{RNET}/2.45
\]

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

\[
E_{\text{AMIN}} = 0.6108 \times \exp\left(\frac{17.27 \times T_{\text{MIN}}}{T_{\text{MIN}}+237.3}\right)
\]

\[
E_{\text{AMAX}} = 0.6108 \times \exp\left(\frac{17.27 \times T_{\text{MAX}}}{T_{\text{MAX}}+237.3}\right)
\]

\[
E_A = \frac{E_{\text{AMIN}} + E_{\text{AMAX}}}{2}
\]

\[
P = 101.3 \times \left(\frac{\text{TK}-0.0065 \times \text{Z}}{\text{TK}}\right)^5.256
\]

\[
\Delta = \frac{4098 \times E_A}{(T+237.3)^2}
\]

\[
\Gamma = 1.6286 \times 10^{-3} \times \frac{P}{\Lambda \text{BDA}}
\]

*-----------------------------------------------------*

* 1. Simplification of Vapour Pressure

*-----------------------------------------------------*

\[
\text{IF}(C\text{CLASS.EQ.1}) \text{ THEN}
\]

\[
\text{CORFAC} = 0.61
\]

\[
\text{ELSEIF}(C\text{CLASS.EQ.2}) \text{ THEN}
\]

\[
\text{CORFAC} = 0.61
\]

\[
\text{ELSEIF}(C\text{CLASS.EQ.3}) \text{ THEN}
\]

\[
\text{CORFAC} = 0.55
\]

\[
\text{ELSEIF}(C\text{CLASS.EQ.4}) \text{ THEN}
\]

\[
\text{CORFAC} = 0.016 \times \text{TMIN} + 0.66
\]

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
This method can be described by the formula $E_{To} = c(W \cdot Rs)$

$$P = 101.3 \times \frac{(TK-0.0065 \times Z)}{TK}^{5.256}$$

$$E_{AMIN} = 0.6108 \times \exp\left(\frac{(17.27 \times TMIN)}{(TMIN+237.3)}\right)$$

$$E_{AMAX} = 0.6108 \times \exp\left(\frac{(17.27 \times TMAX)}{(TMAX+237.3)}\right)$$

$$E_{A} = \frac{E_{AMIN} + E_{AMAX}}{2.0}$$

$$DELTA = \frac{(4098 \times E_{A})}{(T+237.3)^{2}}$$

$$GAMMA = 1.6286 \times 10^{-3} \times \frac{(P/\Lambda bda)}{2.0}$$

$$RS = RSHO / 2.45$$

$$W = \frac{DELTA}{(DELTA+GAMMA)}$$

$$C = 1.066 - 0.0013 \times RHMEAN + 0.045 \times U2M - 0.0002 \times RHMEAN \times U2M - 0.0000315 \times RHMEAN \times U2M$$

$$RADRAD = C \times (W \cdot RS)$$

This method is described by the formula $E_{To} = 1.26 \times W \times (Rn-G)$

$$P = 101.3 \times \frac{(TK-0.0065 \times Z)}{TK}^{5.256}$$

$$E_{AMIN} = 0.6108 \times \exp\left(\frac{(17.27 \times TMIN)}{(TMIN+237.3)}\right)$$

$$E_{AMAX} = 0.6108 \times \exp\left(\frac{(17.27 \times TMAX)}{(TMAX+237.3)}\right)$$

$$E_{A} = \frac{E_{AMIN} + E_{AMAX}}{2.0}$$

$$DELTA = \frac{(4098 \times E_{A})}{(T+237.3)^{2}}$$

$$GAMMA = 1.6286 \times 10^{-3} \times \frac{(P/\Lambda bda)}{2.0}$$

$$W = \frac{DELTA}{(DELTA+GAMMA)}$$

$$RNSHO = (1-\alpha) \times RSHO$$

Parameterization of emissivity according to Idso and Jackson (1969)

$$EPS = -0.02 + 0.261 \times \exp(-7.77E-4 \times T^{2})$$

$$RNallon = (0.9 \times (RSF/100) + 0.1) \times EPS \times \Sigma ma \times \left(\frac{(TKM^{2} + TKMIN^{2})}{2.0}\right)$$

Final calculation of $R_{NET}$, the net radiation

$$R_{NET} = RNSHO - RNallon$$

$R_{NET}$ in $MJ/m^{2}d$ $\rightarrow$ $R_{NET}$ in $mm/d$

$$R_{NET} = \frac{R_{NET}}{2.45}$$

$$RADPRI = 1.26 \times W \times R_{NET}$$
**TEMPERATURE METHODS**

---

**Standardization of Relative Sunshine Fraction only**

```plaintext
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 extraterrestrial radiation, Ra**

```plaintext
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))
```

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

**Parameterization of emissivity according to Idso and Jackson (1969)**

```plaintext
EPS = -0.02+0.261*EXP(-7.77E-4*T**2)
RNLOM = (0.9*RSMEAN+0.1)*EPS*SIGMA*
   ((TKMAX**4+TKMIN**4)/2.0)
```

**Calculation of RNET, the net radiation**

```plaintext
RNET = RNSHO-RNLOM
```

**RNET in MJ/m².d → RNET in mm/d**

```plaintext
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 \times \exp\left(\frac{17.27 \times TMIN}{TMIN + 237.3}\right) \\
EAMAX = 0.6108 \times \exp\left(\frac{17.27 \times TMAX}{TMAX + 237.3}\right) \\
EA = \frac{EAMIN + EAMAX}{2.0} \\
P = 101.3 \times \left(\frac{TK - 0.0065 \times Z}{TK}\right)^{5.256} \\
DELTA = \frac{4098 \times EA}{(T + 237.3)^2} \\
GAMMA = 1.6286 \times 10^{-3} \times \left(\frac{P}{\Lambda}\right) \\
GAMMAK = GAMMA \times (1 + 0.347 \times U2M) \\

*——— Final calculation of radiation term

\[
RATERM = \frac{DELTA}{DELTA + GAMMAK} \times (RNET - G) \\

*——— Final calculation of aerodynamic term

\[
AETERM = \frac{GAMMA}{DELTA + GAMMAK} \times \left(\frac{936.3}{(T + 274.3)}\right) \times U2M \times VPDM \\

*——— Final calculation of reference évapotranspiration

\[
TEMEXT = RATERM + AETERM
\]
* A. THE RADIATION TERM

************ 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 extraterrestrial 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

Parameterization of emissivity according to Idso and 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/m^2/day --> RNET in mm/day

RNET = RNET/2.45
### Calculation of other parameters and variables relevant for radiation and aerodynamic term

\[
\begin{align*}
E_{\text{AMIN}} &= 0.6108 \times \exp\left(\frac{17.27 \times T_{\text{MIN}}}{T_{\text{MIN}} + 237.3}\right) \\
E_{\text{AMAX}} &= 0.6108 \times \exp\left(\frac{17.27 \times T_{\text{MAX}}}{T_{\text{MAX}} + 237.3}\right) \\
E_A &= \frac{E_{\text{AMIN}} + E_{\text{AMAX}}}{2.0} \\
P &= 101.3 \times \left(\frac{(T_K - 0.0065 \times Z)}{T_K}\right)^{5.256} \\
\Delta &= \frac{4098 \times E_A}{(T + 237.3)^2} \\
\Gamma &= 1.6286 \times 10^{-3} \times \frac{P}{\Lambda}\end{align*}
\]

**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:

\[
\begin{align*}
\text{IF}(\text{RH}. \text{LT}. 40.0) \text{ THEN} \\
\quad \text{RHMEAN} &= 25.0 \\
\text{ELSEIF} \quad (\text{RH}. \text{GE}. 40.0. \text{AND}. \text{RH}. \text{LT}. 55.0) \text{ THEN} \\
\quad \text{RHMEAN} &= 48.0 \\
\text{ELSEIF} \quad (\text{RH}. \text{GE}. 55.0. \text{AND}. \text{RH}. \text{LT}. 70.0) \text{ THEN} \\
\quad \text{RHMEAN} &= 63.0 \\
\text{ELSEIF} \quad (\text{RH}. \text{GE}. 70.0) \text{ THEN} \\
\quad \text{RHMEAN} &= 85.0 \\
\text{ENDIF}
\end{align*}
\]

\[
\begin{align*}
\text{ED} &= E_A \times (\text{RHMEAN}/100.0) \\
\text{VPD} &= E_A - \text{ED}
\end{align*}
\]

For the daytime wind (07.00–19.00 hours) values the following classification is applied.

- **U2 low**: 0–2 m/s, 1.0 m/s used in model.
- **U2 moderate**: 2–5 m/s, 3.5 m/s used in model.
- **U2 high**: 5–8 m/s, 6.5 m/s used in model.
- **U2 very high**: >8 m/s, 10.0 m/s used in model.

\[
\begin{align*}
\text{IF}(\text{U2M}. \text{LT}. 2.0) \text{ THEN} \\
\quad U2 &= 1.0 \\
\text{ELSEIF} \quad (\text{U2M}. \text{GE}. 2.0. \text{AND}. \text{U2M}. \text{LT}. 5.0) \text{ THEN} \\
\quad U2 &= 3.5 \\
\text{ELSEIF} \quad (\text{U2M}. \text{GE}. 5.0. \text{AND}. \text{U2M}. \text{LT}. 8.0) \text{ THEN} \\
\quad U2 &= 6.5 \\
\text{ELSEIF} \quad (\text{U2M}. \text{GE}. 8.0) \text{ THEN} \\
\quad U2 &= 10.0 \\
\text{ENDIF}
\end{align*}
\]

\[
\begin{align*}
\Gamma_{\text{MK}} &= \Gamma \times (1 + 0.347 \times U2)
\end{align*}
\]
*------ Final calculation of radiation term

\[ \text{RATERM} = \frac{\text{DELTA}}{\text{DELTA} + \text{GAMMAK}} \times (\text{RNET} - \text{G}) \]

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

\[ \text{AETERM} = \frac{\text{GAMMA}}{\text{DELTA} + \text{GAMMAK}} \times \left( \frac{936.3}{(T + 274.3)} \right) \times \frac{U_2 \times \text{VPD}}{\text{RATERM} + \text{AETERM}} \]

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

\[ \text{TEMSTA} = \text{RATERM} + \text{AETERM} \]
*— — Calculation of parameters and variables relevant for radiation and aerodynamic term

\[
\begin{align*}
\text{EAMIN} &= 0.6108 \times \exp\left(\frac{17.27 \times \text{TMIN}}{\text{TMIN} + 237.3}\right) \\
\text{EAMAX} &= 0.6108 \times \exp\left(\frac{17.27 \times \text{TMAX}}{\text{TMAX} + 237.3}\right) \\
\text{EA} &= \frac{\text{EAMIN} + \text{EAMAX}}{2.0} \\
\text{P} &= 101.3 \times (\frac{\text{TK} - 0.0065 \times \text{Z}}{\text{TK}})^{5.256} \\
\text{DELTA} &= \frac{4098 \times \text{EA}}{(\text{T} + 237.3)^2} \\
\text{GAMMA} &= 1.6286 \times 10^{-3} \times (\frac{\text{P}}{\text{LABDA}})
\end{align*}
\]

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

\[
\text{ED} = \text{CORFAC} \times \exp\left(\frac{17.27 \times \text{TMIN}}{\text{TMIN} + 237.3}\right)
\]

\[
\text{VPD} = \text{EA} - \text{ED}
\]

* A. THE RADIATION TERM

***********************************************************
* Calculation of net radiation ————
***********************************************************

IF (METHOD.EQ.1) THEN

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

IF (CLASS.EQ.1.AND. TEMCLASS.EQ.1) THEN
\[
\text{RSHO1} = 0.45 \times \text{TMAX} + 3.3
\]
ELSEIF (CLASS.EQ.1.AND. TEMCLASS.EQ.2) THEN
\[
\text{RSHO1} = 0.125 \times \text{TMAX} + 14.4
\]
ELSEIF (CLASS.EQ.1.AND. TEMCLASS.EQ.3) THEN
\[
\text{RSHO1} = 1.56 \times \text{TMAX} - 39.4
\]
ELSEIF (CLASS.EQ.2.AND. TEMCLASS.EQ.1) THEN
\[
\text{RSHO1} = 0.62 \times \text{TMAX} + 0.69
\]
ELSEIF (CLASS.EQ.2.AND. TEMCLASS.EQ.2) THEN
\[
\text{RSHO1} = 0.16 \times \text{TMAX} + 0.69
\]
ELSEIF (CLASS.EQ.2.AND. TEMCLASS.EQ.3) THEN
\[
\text{RSHO1} = 0.17 \times \text{TMAX} + 13.9
\]
ELSEIF (CLASS.EQ.3.AND. TEMCLASS.EQ.1) THEN
\[
\text{RSHO1} = 0.66 \times \text{TMAX} + 2.4
\]
ELSEIF (CLASS.EQ.3.AND. TEMCLASS.EQ.2) THEN
\[
\text{RSHO1} = 0.31 \times \text{TMAX} + 11.2
\]
ELSEIF (CLASS.EQ.3.AND. TEMCLASS.EQ.3) THEN
\[
\text{RSHO1} = 0.31 \times \text{TMAX} + 11.2
\]
ELSEIF (CLASS.EQ.4.AND. TEMCLASS.EQ.1) THEN
\[
\text{RSHO1} = 0.41 \times \text{TMAX} + 8.3
\]
ELSEIF (CLASS.EQ.4.AND. TEMCLASS.EQ.2) THEN
\[
\text{RSHO1} = 0.37 \times \text{TMAX} + 8.9
\]
ELSEIF (CLASS.EQ.4.AND. TEMCLASS.EQ.3) THEN
\[
\text{RSHO1} = 0.33 \times \text{TMAX} + 10.25
\]
ENDIF
**Calculation of extraterrestrial radiation, RA**

This parameter is needed to calculate RSF from RSHO

\[
\begin{align*}
\text{PHI} &= (\text{LAT}/360)*2*3.1416 \\
\text{J} &= \text{INT}(30.42*\text{MO}-15.23) \\
\text{DR} &= 1 + 0.033 * \cos((((2*3.1416)/365) * J) \\
\text{DEL} &= 0.4093 * \sin(((2*3.1416)*(284+J))/365) \\
\text{OMEGA} &= \arccos(-\tan(\text{PHI}) \cdot \tan(\text{DEL}))
\end{align*}
\]

\[
\begin{align*}
\text{RA} &= \left( (24*60)/3.1416 \right) * 0.0820 * \text{DR} \cdot (\text{OMEGA} \cdot \sin(\text{PHI}) \cdot \sin(\text{DEL})) \\
&+ \cos(\text{PHI}) \cdot \cos(\text{DEL}) \cdot \sin(\text{OMEGA})
\end{align*}
\]

IF(CCLASS.GE.3) THEN
  \[
  \begin{align*}
  A &= 0.25 \\
  B &= 0.45
  \end{align*}
  \]
ELSEIF(CCLASS.EQ.1.AND.T.GE.30.0) THEN
  \[
  \begin{align*}
  A &= 0.29 \\
  B &= 0.42
  \end{align*}
  \]
ELSE
  \[
  \begin{align*}
  A &= 0.18 \\
  B &= 0.55
  \end{align*}
  \]
ENDIF

RSF = (RSH01/(B*RA)) - A/B
IF(RSF.GT.0.95) THEN
  RSF = 0.95
ELSEIF(RSF.LT.0.10) THEN
  RSF = 0.10
ENDIF
RSHO = RSH01
GOTO 10
ENDIF

*********************************************************************************************

*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
  
96
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 extraterrestrial 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(METH0D.EQ.3) THEN
        RELHUM = (ED/EA)*100.0
    IF(CCLASS.EQ.1) THEN
RSH03 = 0.18 * RELHUM + 27.0
ELSEIF (CCLASS.EQ.2) THEN
  RSH03 = 0.15 * RELHUM + 29.3
ELSEIF (CCLASS.EQ.3) THEN
  RSH03 = 0.13 * RELHUM + 27.0
ELSEIF (CCLASS.EQ.4) THEN
  RSH03 = 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
  RSH = (0.42 * TMAX + 32.4) / 100.0
ELSEIF(CCLASS.EQ.1.AND.TEMCLAS.EQ.2) THEN
  RSH = (0.25 * TMAX + 40.7) / 100.0
ELSEIF(CCLASS.EQ.1.AND.TEMCLAS.EQ.3) THEN
  RSH = (9.4 * TMAX - 298.6) / 100.0
ELSEIF(CCLASS.EQ.2.AND.TEMCLAS.EQ.1) THEN
  RSH = (1.09 * TMAX + 28.5) / 100.0
ELSEIF(CCLASS.EQ.2.AND.TEMCLAS.EQ.2) THEN
  RSH = (0.57 * TMAX + 43.1) / 100.0
ELSEIF(CCLASS.EQ.2.AND.TEMCLAS.EQ.3) THEN
  RSH = (0.20 * TMAX + 51.4) / 100.0
ELSEIF(CCLASS.EQ.3.AND.TEMCLAS.EQ.1) THEN
  RSH = (1.37 * TMAX + 30.6) / 100.0
ELSEIF(CCLASS.EQ.3.AND.TEMCLAS.EQ.2) THEN
  RSH = (0.40 * TMAX + 56.4) / 100.0
ELSEIF(CCLASS.EQ.3.AND.TEMCLAS.EQ.3) THEN
  RSH = (0.013 * TMAX + 67.3) / 100.0
ELSEIF(CCLASS.EQ.4.AND.TEMCLAS.EQ.1) THEN
  RSH = (0.50 * TMAX + 61.7) / 100.0
ELSEIF(CCLASS.EQ.4.AND.TEMCLAS.EQ.2) THEN
  RSH = (0.30 * TMAX + 70.6) / 100.0
ELSEIF(CCLASS.EQ.4.AND.TEMCLAS.EQ.3) THEN
  RSH = (0.35 * TMAX + 70.3) / 100.0
ENDIF
RSH0 = RSH03
GOTO 10
ENDIF

10 IF (RSH0.LT.0.0) THEN
  RSH0 = 2.0
ENDIF
RNSHO = (1 - ALPHA) * RSH0
Parameterization of emissivity according to Idso and Jackson (1969)

\[
\begin{align*}
\text{EPS} & = -0.02 + 0.261 \times \exp(-7.77 \times 10^{-4} \times T^2) \\
\text{RNロン} & = (0.9 \times (\text{RSF}) + 0.1) \times \text{EPS} \times \text{SIGMA} \\
& \quad \times \left(\frac{(T_{\text{MAX}}^4 + T_{\text{MIN}}^4)}{2.0}\right)
\end{align*}
\]

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

\[
\text{RNET} = \text{RNSHO} - \text{RNロン}
\]

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

\[
\text{RNET} = \frac{\text{RNET}}{2.45}
\]

*** Standardization of wind values ***

*—— Standardization of wind values *

** For the daytime wind (07.00-19.00 hours) values the following 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.

\[
\begin{align*}
\text{IF} & (U2. \text{LT.} 2.0) \text{ THEN} \\
\text{U2} & = 1.0 \\
\text{ELSEIF} & (U2. \text{GE.} 2.0 \text{ AND} \text{U2.} \text{LT.} 5.0) \text{ THEN} \\
\text{U2} & = 3.5 \\
\text{ELSEIF} & (U2. \text{GE.} 5.0 \text{ AND} \text{U2.} \text{LT.} 8.0) \text{ THEN} \\
\text{U2} & = 6.5 \\
\text{ELSEIF} & (U2. \text{GT.} 8.0) \text{ THEN} \\
\text{U2} & = 10.0 \\
\text{ENDIF}
\end{align*}
\]

\[
\text{GAMMA_ロン} = \text{GAMMA} \times (1 + 0.347 \times \text{U2})
\]

*—— Final calculation of radiation term

\[
\text{RATERM} = \left(\frac{\Delta}{\Delta + \text{GAMMA_ロン}}\right) \times (\text{RNET} - G)
\]

*—— Final calculation of aerodynamic term

\[
\text{AETERM} = \left(\frac{\text{GAMMA}}{\Delta + \text{GAMMA}}\right) \times \left(\frac{936.3}{T+274.3}\right) \times U2 \times \text{VPD}
\]

\[
\text{TEMSIM} = \text{RATERM} + \text{AETERM}
\]
*——Calculation of extraterrestrial radiation, $Ra$

$$
\begin{align*}
\Phi &= (\text{LAT}/360) \times 2 \times 3.1416 \\
J &= \text{INT}(30.42 \times \text{MO} - 15.23) \\
\text{DR} &= 1 + 0.033 \times \cos(((2 \times 3.1416) / 365) \times J) \\
\text{DEL} &= 0.4093 \times \sin(((2 \times 3.1416) \times (284 + J)) / 365) \\
\Omega &= \arccos(-\tan(\Phi) \times \tan(\text{DEL})) \\
\text{RA} &= ((24 \times 60) / 3.1416) \times 0.0820 \times \text{DR} \times (\Omega \times \sin(\Phi) \times \sin(\text{DEL}) \\
&\quad + \cos(\Phi) \times \cos(\text{DEL}) \times \sin(\Omega))
\end{align*}
$$

*——Hargreaves Formula

$$
\text{TEMHAR} = (0.0023 \times \text{RA} \times (\text{DEL})^{0.5} \times (\text{T} + 17.8)) / 2.45
$$

*-----------------------------------------------*
* OUTPUT                                       *
*-----------------------------------------------*

*——Write various types of potential

Write various types of potential evapotranspiration to output file

```
WRITE(41, '(1X,F7.4,1X,I2,9(1X,F5.2))') STATNR, MO, RADEXT, 
RASTA, 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 weighting 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 Address: 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
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

For the daytime wind (07.00-19.00 hours) values the following classification is applied.

- **U2 low**: 0-2 m/s, 1.0 m/s used in model. class 1
- **U2 moderate**: 2-5 m/s, 3.5 m/s used in model. class 2
- **U2 high**: 5-8 m/s, 6.5 m/s used in model. class 3
- **U2 very high**: >8 m/s, 10.0 m/s used in model. class 4

```fortran
IF(U2CIAS(K).EQ.1) THEN
   U2(K) = 1.0
ELSEIF (U2CIAS(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
```

Calculation of the aerodynamic term (without weighting factor)

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

* Write output to file

```fortran
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 $W_1 = \delta/\delta + \gamma$ and $W_2 = \gamma/\delta + \gamma'$ of the proposed combination equation. An example of the input file is also given.

PROGRAM DELGAM

C************************************************************
C This program calculates $W_1 = \Delta/\Delta + \Gamma K$ and $W_2 = \Gamma/\Delta + \Gamma K$. $W_1$ is the weighting factor for the effect of $\gamma$ radiation on $E_0$, whereas $W_2$ is a measure of the effect of $\gamma$ the aerodynamic term on $E_0$.
C
C Author: Anne Verhoef
C Address: 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 output file
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',/)

105
* 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

    106
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
<table>
<thead>
<tr>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
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</tr>
<tr>
<td>250.0</td>
</tr>
<tr>
<td>500.0</td>
</tr>
<tr>
<td>750.0</td>
</tr>
<tr>
<td>1000.0</td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
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<td>3500.0</td>
</tr>
<tr>
<td>4000.0</td>
</tr>
<tr>
<td>2.0</td>
</tr>
<tr>
<td>4.0</td>
</tr>
<tr>
<td>6.0</td>
</tr>
<tr>
<td>8.0</td>
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<td>38.0</td>
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</tbody>
</table>
APPENDIX 4.

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

This output file 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 station number. 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 output files.
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 station number, 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
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
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,F6.1,1X,F5.1,1X,
F6.2,1X,I4,1X,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

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=1.0E-20)

INTEGER MO(1000),METHOD
REAL STNR(IOOO),REXT(IOOO),RSTA(IOOO),RSIM(IOOO)
REAL RRAD(IOOO),RPRI(IOOO),TEXT(IOOO),TSTA(IOOO)
REAL TSIM(IOOO),THAR(IOOO),X(IOOO),Y(IOOO),ERROR(IOOO)
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),
RRA(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

114
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*SQR(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