Ch. 2: Weather and reference ET

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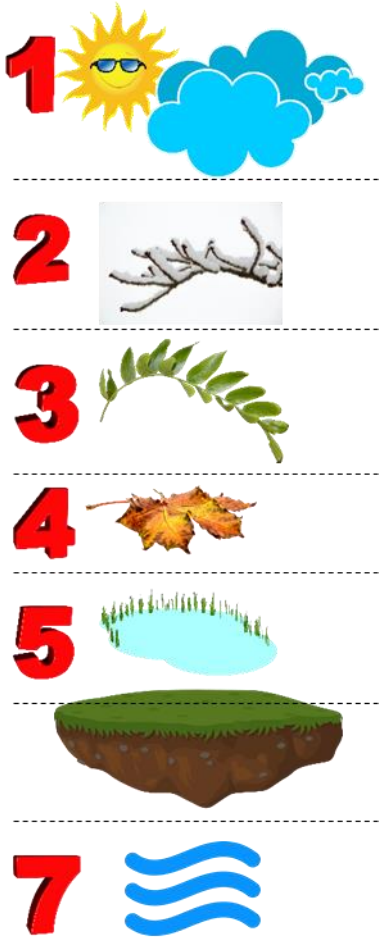
2 Weather and reference ET

2.1 Introduction



As described in Chapter 1, the Daisy model consist of several strictly ordered **compartments**, from top to bottom:

1. The atmosphere, or weather layer.
2. The snow pack.
3. The canopy.
4. The litter layer.
5. The surface, including ponded water.
6. The soil, described in chapters 3-8.
7. The lower boundary, such as groundwater or aquifer, described together with soil.

This chapter deals with the description of the first compartment, and more specifically we describe the different models for the calculation of reference evapotranspiration, together with the required weather data. The requirement for input data differ between the models.

2.2 Weather data

The types and resolution of weather data to apply in a model simulation depends on the requirement of the research question and the sub-models to be used. In Daisy, the minimum weather data requirement is daily values of global radiation, air temperature and precipitation. As shown in Table 2.1, this combination will allow calculation of evapotranspiration using a Makkink reference evapo-transpiration (ET_r) model only. Reference evapotranspiration may also be calculated by the user and given as input.

In order to calculate the distribution of radiation over the day and day length, information on latitude, longitude, time zone and elevation is required, and this is also specified in the weather file.

However, much more detailed weather information can be utilized by the model. The average daily air temperature can be exchanged for daily minimum and maximum temperatures, and the dataset extended with wind speed and vapour pressure (or relative humidity). The same data can be supplied hourly (except min and max temperatures). Such data increase the choice of ET_r-models that may be selected (Table 2.1 and section 2.3). Detailed hourly data is also relevant for calculation of site-specific potential evapotranspiration or in case one of the non-

Table 2.1. Methods to specify reference evapotranspiration and associated data requirements. A site specific potential evapotranspiration can be calculated instead if on-site measurements are available.

Variable	Reference Evapotranspiration					Potential ET
	Weather file	Makkink equations	Hargreaves	FAO-PM, daily	FAO-PM, hourly	PM
Global radiation	(whatever)	daily	daily	daily	hourly	hourly
Temperature	(whatever)	daily average	T_{min}/T_{max}	daily average or T_{min}/T_{max}	hourly	hourly
Wind speed	not used	not used	not used	daily average	hourly	hourly
Relative humidity	not used	not used	not used	daily average	hourly	hourly
ET_r specified by the user	daily or hourly					
Measurement conditions	Weather station above FAO standard grass					Based on measurements at study site.

standard soil-vegetation-atmosphere-transfer (svat) models are selected (PMSW (van der Keur et al., 2001) or SSOC (Plauborg et al., 2010))

If ET_r is calculated according to the FAO recommendations for the Penman-Monteith-equation, the above data will suffice. However, a cloudiness factor and ground heat flux may be specified in the weather file if the user does not wish to use the standard calculation methods.

Diffuse radiation and CO_2-level [ppm] can be given as input but is only used in the SSOC-model (Appendix 3.X[1]). If diffuse radiation is not available, it is calculated by the model (Appendix 3.X).

The parameters and variables that may be included in the weather file are described in the weather chapter of the reference manual and additional information is described in Appendix A of the reference manual distributed with the model. Samples of weather files are found in the Daisy sample library installed with the model (subscript .dwf).

2.2.1 Precipitation

It is assumed that the precipitation (P) applied in the weather file is corrected to ground level. For historical reasons, it is possible to specify monthly correction factors [*PrecipCorrect*], but use of dynamic corrections (Vejen et al., 2014 for Danish conditions, otherwise Goodison et al., 1998) are recommended.

Until version 6.09, precipitation was, by default, considered to be snow if the air temperature is below -2°C and rain of the temperature is above 2°C. From version 6.09 onwards, precipitation is considered snow under 0 °C, in line with Allerup et al. (1996). In between the two values, the fraction of snow is interpolated. These parameters can be set by user. Note, that for the correction of precipitation to ground level, Vejen et al. (2014) specify the snow and rain-boundaries as -2°C and 0°C, respectively.

Precipitation can be scaled using a constant or monthly factors multiplied onto the input file values [PrecipScale]. Precipitation is the main input to the water balance.

2.2.2 Wind speed

The height of the wind measurements is assumed to be 2 m (u_2), and if measured at a different height, data should be corrected to 2 m (also taking into account shelter effects) before it is entered into the weather file. Screen height (z_m) to be specified in the weather file is therefore by default 2 m. The wind speed is used to calculate reference evapotranspiration (and/or potential evapotranspiration).

2.2.3 Global radiation

Global radiation (S_i) is required for both evapotranspiration calculation and photosynthesis. If only daily values are available, the radiation is distributed over the day according to the distribution of extra-terrestrial radiation over the day.

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[1] Appendix 3.X is not yet available. Presently, the best sources are https://daisy.ku.dk/about-daisy/projects/safir/ and Plauborg et al. (2010).

The calculation of daily extra-terrestrial radiation is shown in equation (2.14) and the modifications done for shorter periods are described in Section 2.3.3. The fraction of radiation occurring in a specific time period is multiplied onto the measured daily global radiation.

2.2.4 Temperature and humidity

Air temperature (T_a) is the upper boundary for heat transport calculations and is essential for all heat-related processes in the model. If only daily average value is given, this value is used in the model for the whole day. If daily minimum and maximum temperatures (T_{min}/T_{max}) are specified, it is assumed that T_{max} occurs at 15.00 and T_{min} occurs at sunrise. The temperature between sunrise and 15.00 hours is calculated by simple interpolation. To obtain temperatures before sunrise and after 15.00 hours, it is assumed that the day before and the day after are similar to the present day, and temperatures area again obtained by interpolation.

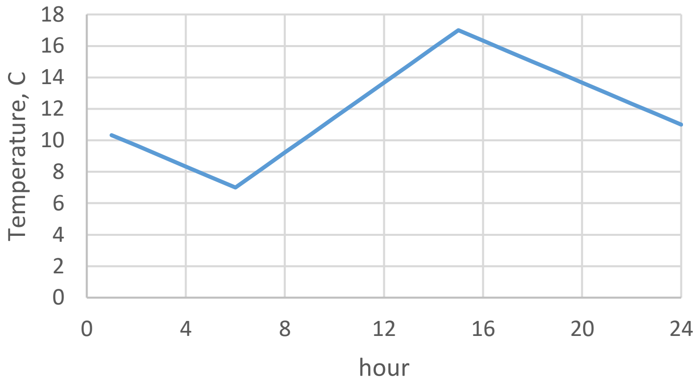


Figure 2.1. Temperature distribution over a day, assuming a minimum temperature of 7 degrees, a maximum temperature of 17 degrees and sunrise at 6.00 hours.

Temperature can be offset by a constant or monthly values [*TempOffset*].

It is implicitly assumed that the actual humidity (e_a)(either vapour pressure or relative humidity) is measured at 2 m's height. There is thus not a separate correction for measurement height here.

2.2.5 Other weather related data

Lower boundary condition for soil heat

Lower boundary condition for heat calculations in soil may be calculated based on the temperature data. This is described in Chapter 5 and Appendix 5.

Deposition

Deposition of ammonium and nitrate-N is specified in the Daisy weather file. Dry deposition is specified as a kg NH_4-N ha^{-1} year^{-1} and kg NO_3-N ha^{-1} year^{-1} [or kg m^{-2} day^{-1}]. Wet deposition of the same two compounds is specified as a concentration, typically ppm [mg l^{-1}]. The rates should be calculated based on measurements. In Denmark, annual estimates are available from DCE (Institute for environmental science), Aarhus University. Precipitation data is required to calculate the mass fluxes for the wet deposition.

2.3 Calculation of reference evapotranspiration

If reference evapotranspiration is not supplied to the model by the user together with other “weather data”; it can be calculated by the model as “best option” where the model selects a model or the reference evapotranspiration model can be specified by the user.

The model will, if the reference evapotranspiration model is not specified, choose the values specified in the weather file as first priority and, if that is not available, use the best model for the data provided, i.e.

- the FAO-Penman Monteith equation for hourly values of global radiation, wind speed, vapour pressure and temperature (Allen et al., 2006),
- the FAO-Penman Monteith equation for daily values of the same parameters as above (Allen et al., 1998),
- The Hargreaves model (Hargreaves and Samani, 1985), if T_{min} and T_{max}-values are specified in the weather file (together with global radiation), or
- the deBruin 1987-parameterisation of the Makkink model, which only require global radiation and temperature (de Bruin, 1987).

Please note, that the default FAO-PM-parameterisation now includes the ASCE/Kjaersgaard-calculation of extra-terrestrial radiation cloudiness (see below). Also, note that earlier, the Makkink-parameterisation by Hansen (1984) was the default Makkink model.

All parameterisations not shown here are available in Appendix 2.2.

2.3.1 The FAO Penman Monteith equation

The Penman-Monteith formula is specified as shown in eq. (2.1), where the first term is governed by radiation and the second of the aerodynamic properties.

$$E_r = \frac{\Delta\left(R_n - G\right)}{\lambda\left(\Delta + \gamma\left(1 + r_c / r_a\right)\right)} + \frac{\rho c_p\left(e_s - e_a\right) / r_a}{\lambda\left(\Delta + \gamma\left(1 + r_c / r_a\right)\right)} \tag{2.1}$$

Where

R_n = net radiation flux at the crop surface [W m^{-2}]

G = soil heat flux density [W m^{-2}]

ρ = air density [kg m^{-3}]

c_p = the specific heat of moist air at constant pressure, $1.013 \cdot 10^3$ [J kg^{-1} K^{-1}]

e_s = saturation vapour pressure [Pa],

e_a =actual vapour pressure [Pa]

r_c = crop canopy resistance [s m^{-1}]

r_a = aerodynamic resistance [s m^{-1}]

Δ = slope vapour pressure curve [Pa K^{-1}]

γ = psychrometric constant [Pa °K^{-1}]

λ = latent heat of vaporization [J kg^{-1}].

E_r = [kg m^{-2} s^{-1}] or [mm s^{-1}]

Saturation vapour pressure

e_s, the saturation vapour pressure [Pa] is calculated as:

$$e_s = 611 \cdot \exp\left(\frac{17.27\left(T_a - 273.15\right)}{T_a - 35.9}\right) \tag{2.2}$$

where

T_a = air temperature

The slope of the saturation vapour pressure as a function of temperature [Pa K^{-1}] is calculated as:

$$\Delta = \frac{4.098 \cdot 10^3 \cdot e_s}{\left(T_a - 35.9\right)^2} \tag{2.3}$$

Latent heat of vaporization

The latent heat of vaporization [J kg^{-1}] is estimated as:

$$\lambda = \left(2.501 - T_a \cdot 2.361 \cdot 10^{-3}\right) 10^6 \tag{2.4}$$

The psychrometric constant

The psychrometric constant is described as:

$$\gamma = \frac{c_p P}{\varepsilon \lambda} = 1.63 \cdot 10^3 \frac{P}{\lambda} \tag{2.5}$$

Where

c_p = specific heat at constant pressure, 1.013·10^3 [J kg^{-1} K^{-1}],

ε = ratio molecular weight of water vapour/dry air = 0.622,

P = atmospheric pressure [Pa] calculated as shown below:

$$P = 101.3 \cdot 10^3 \left(\frac{293 - 6.5 \cdot 10^{-3} \cdot z}{293}\right)^{5.26} \tag{2.6}$$

z = elevation above sea level [m].

Net radiation

Net radiation, R_n (incoming) is estimated as net incoming shortwave radiation, $R_{n,s}$, minus net outgoing longwave radiation, L_n:

$$R_n = R_{n,s} - L_n \tag{2.7}$$

- Shortwave

The net incoming shortwave radiation is calculated as

$$R_{n,s} = (1 - \alpha) S_i \tag{2.8}$$

α = surface albedo or canopy reflection coefficient (0.23 overall average for grass),

S_i = the global radiation [W m^{-2}],

- Longwave

The net long-wave radiation (outgoing) [W m^{-2}] is calculated as the balance between outgoing and incoming long-wave radiation (calculated according to Brunt, 1932, with default parameterisation by Jensen et al., 1990). Outgoing long-wave radiation is calculated as:

$$L^{out} = \varepsilon_v \cdot \sigma T_a^4 \tag{2.9}$$

ε_v = the emissivity of vegetation (0.99 - 0.94) and soil (range 0.98 - 0.80, default value 0.98),

σ = the Stefan-Boltzmann constant (5.67 10^{-8} [W m^{-2} K^{-4}]),

T_a = mean air temperature [K].

Incoming longwave radiation is estimated as full reflection from the cloudy area and depending on the emissivity of the atmosphere for the clear sky area:

$$L^{in} = (1 - f_c)\varepsilon_v \sigma T_a^4 + f_c \varepsilon_a \sigma T_a^4 \tag{2.10}$$

f_c = adjustment for cloud cover,

ε_a = the effective emissivity of the atmosphere, calculated according to the Brunt formula (Brunt, 1932):

$$\varepsilon_a = a_e + b_e \sqrt{e_a} \tag{2.11}$$

where the standard parametrization a_e = 0.64 and b_e = 0.14 (FAO, 1990) is adopted as default and e_a is vapour pressure [kPa].

The net longwave (outgoing) equation thus becomes:

$$\begin{aligned} L_n &= f_c(\varepsilon_v - \varepsilon_a)\sigma T_a^4 = f_c\left(0.98 - (0.64 - 0.14\sqrt{e_a})\right)\sigma T_a^4 \\ &= f_c\left(0.34 - 0.14\sqrt{e_a}\right)\sigma T_a^4 \end{aligned} \tag{2.12}$$

Other formulas for calculation of effective emissivity of longwave radiation are available and can be specified under [bioclimate]. The available long-wave net-radiation models are described in Appendix 2.3.

Cloudiness factor

The cloudiness factor is estimated as:

$$f_c = a_c \frac{S_i}{S_{io}} + (1 - a_c) \tag{2.13}$$

where S_{io} is the extraterrestrial radiation at the soil surface and a_c and a_s are empirical constants (Allen et al., 1998).

The recommended value by Allen et al. (1998) for a_c is 1.35 and the value is included in the "cloudiness"-submodel "FAO56". However, (Kjaersgaard et al., 2007) found that both hourly and daily R_n were overestimated when using this model calibration coefficient over short well-watered grass. Jensen et al. (1990) and Kjærsgaard et al. (2007a) recommended a value of a_c of 1, which is now included as an optional cloudiness model, which can be specified under [bioclimate].

Irrespective of method, the cloudiness at the end of the day is extrapolated to the following night. However, which cloudiness to extrapolate depends on a range of criteria that can be set. These are 1) The extra-terrestrial radiation must be higher than a value (default 0), 2) The global radiation must be higher than a value (default 0), 3) the solar elevation angle must be higher that a value, 4) the S_i/S_{io}-ratio must be higher than a value, 5) the time to sunset should at least be a certain value (default 0), and 6) the time after sunrise should at least be a certain value before a new cloudiness value is calculated.

Extra-terrestrial radiation

Method 1: FAO56, daily calculation

Daisy includes two methods to calculate extra- terrestrial radiation at ground level. The first method (Allen et al., 1998)) calculates $S_{io} = S_e * (0.75 + 2*10^{-5} z)$, z being the station elevation above sea level, but the last term is not implemented here. So, in short, $S_{io} = a_s * S_e$, where $a_s = 0.75$.

Estimation of extraterrestrial radiation, S_e, during the day requires knowledge of latitude and date and time:

$$S_e = G_{sc} d_r \left(\omega_s \sin(\delta) \sin(\varphi) + \cos(\delta) \cos(\varphi) \sin(\omega_s) / \pi \right) \tag{2.14}$$

G_{sc} = solar constant = $1.3667 \cdot 10^3$ [W m^{-2}]

d_r = inverse relative Earth-Sun distance $= 1 + 0.033 \cos\left(\frac{2\pi J}{365}\right)$

ω_s = the sunset hour angle $= \arccos(-\tan\varphi \tan\delta)$ [rad]

δ = solar declination $= 0.409 \sin\left(\frac{2\pi J}{365} - 1.39\right)$ [rad]

J = the number of day in the year (ordinal day)

φ = latitude

Hourly calculation of incoming radiation

For hourly calculations of incoming radiation, ω_s and $sin(\omega_s)$ in equation (2.14) changes to (ω_2- ω_1) and $(sin(\omega_2)-sin(\omega_1))$, where ω_1 is the solar time angle at the beginning of the period and ω_2 is the solar time angle at the end of the period [rad]

$$\omega_1 = \omega - \frac{\pi t_1}{24}; \; \omega_2 = \omega + \frac{\pi t_1}{24} \tag{2.15}$$

Where ω is the solar time angle at midpoint of the hourly time step [rad], and t_1 is the length of the calculation period [hr].

The solar time angle at the midpoint of the period is:

$$\omega = \frac{\pi}{12}\left[\left(t + \frac{24}{360}\left(L_z - L_m\right) + S_c\right) - 12\right] \tag{2.16}$$

Where

t = standard clock time at the midpoint of the period [hr].

L_z = longitude of the centre of the local time zone [degrees west of Greenwich].

L_m = longitude of the measurement site [degrees west of Greenwich]

S_c =seasonal correction for solar time.

If the sun is below the horizon ($\omega < -\omega_s$ or $\omega > \omega_s$), S_e is zero.

According to Allen et al. (1998), the seasonal correction for solar time is:

$$\begin{aligned} S_c &= 0.1645\sin(2b) - 0.1255\cos(b) - 0.025\sin(b) \\ b &= \frac{2\pi(J-81)}{365} \end{aligned} \tag{2.17}$$

Where J is the number of day in the year.

The final expression for calculation of radiation over an hour or a shorter period thus looks as follows:

$$R_a = \frac{12}{\pi} G_{sc} d_r \left[\left(\omega_2 - \omega_1\right)\sin\left(\varphi\right)\sin\left(\delta\right) + \cos\left(\varphi\right)\cos\left(\delta\right)\left(\sin\left(\omega_2\right) - \sin\left(\omega_1\right)\right)\right] \tag{2.18}$$

where R_a is in [W m^{-2}] for the period in question.

Daytime is defined with a minimum solar elevation angle of 0.174533 [rad] and a S_i/S_{io}-ratio of 0.3 as standard in the FAO56-model. This cloudiness model with $a_c=1.35$ is implemented as [FAO56]. However, it is also possible to choose a combination of the a_c-value of 1 and a combination of a minimum solar elevation angle of 0 [rad] and a minimum extraterrestrial radiation of 25 [W m^{-2}] as recommended by Kjaersgaard et al. (2007) [Kjaersgaard].

Method 2: ASCE

The second method is recommended by ASCW-EWRI-2005 (submodel "ASCE") (Allen et al., 2005, Blonquist et al., 2010). The calculations are shown below:

$$S_{io} = S_e\left(K_B + K_D\right) \tag{2.19}$$

$$K_B = 0.98\exp\left[\frac{-1.46\cdot 10^{-3}\cdot P_A}{K_t\sin(\theta)} - 0.075\left(\frac{W_P}{\sin(\theta)}\right)^{0.4}\right] \tag{2.20}$$

$$W_P = 0.14\cdot e_a\cdot P_A + 2.1 \tag{2.21}$$

where
e_a and P_A are in kPa. P_A is atmospheric pressure, already calculated in Daisy.
K_t = 1 for clean air and $\leq$ 0.5 for turbid, dusty, or polluted air. "1" is the standard value.

$$\sin(\theta) = \sin(\delta)\sin(\phi) + \cos(\delta)\cos(\phi)\cos(\omega)$$

ω is calculated from equation 2.14.

K_B can only be calculated when the sun is above the horizon:

$$K_D = \begin{cases} 0.35 - 0.36K_B & \text{for } K_B \geq 0.15 \\ 0.18 + 0.82K_B & \text{for } K_B < 0.15 \end{cases}$$

As for method 1, method 2 is parameterised with the standard a_c-value, a minimum solar elevation angle of 0.174533 [rad] and a S_i/S_{io}-ratio of 0.3 [ASCE] or with $a_c=1$ and a minimum angle of 0 combined with a minimum extra-terrestrial radiation of 25 [W m^{-2}], calibrated for Taastrup, Denmark [Taastrup].

Method 2 provides a better estimate of incoming radiation morning and evening and this results in a better calculation of cloudiness. This has shown to be important when using hourly values, see Figure 2.2.

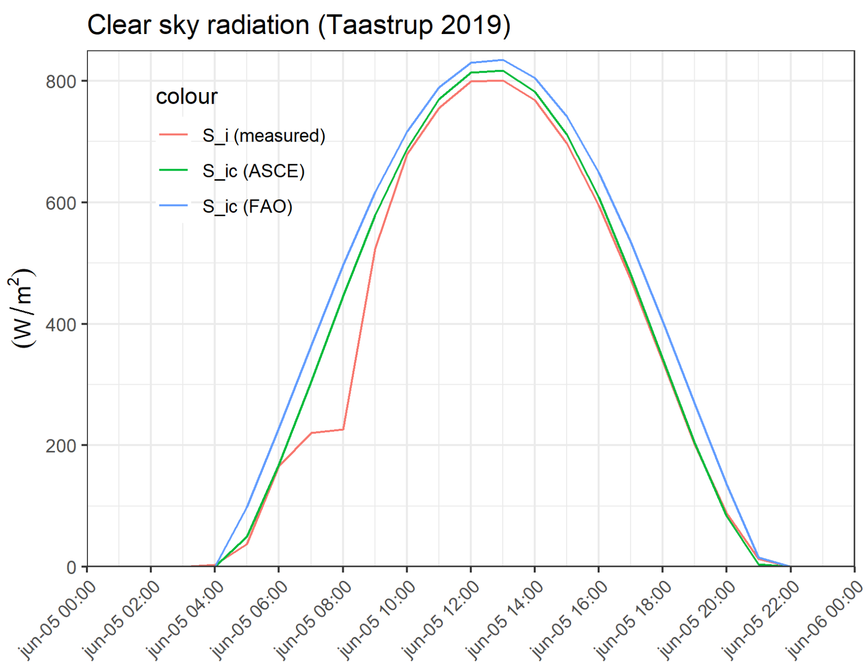


Figure 2.2. Comparison between incoming clear sky shortwave radiation calculated by the standard FAO-method, the ASCE-method and measured data.

Soil heat flux

G, the soil heat flux density may be calculated as $0.1R_n$ during daytime and $0.5R_n$ during night time as recommended for hourly time steps (Allen et al., 1998), set constant (0, as recommended by Allen et al. (1998)) for 1-10-day periods or the soil heat flux calculated by Daisy may be used in the calculation, which was default before version. 6.11. The soil heat flux is calculated by Daisy using the heat transfer equations described in Chapter 5.

Aerodynamic resistance

The aerodynamic resistance for the reference vegetation is estimated as:

$$r_a = \frac{208}{u_2} \qquad (2.22)$$

where u_2 is the wind speed at 2 m's height. The corresponding canopy resistance is assumed to be r_c = 70 s m^{-1} (Allen et al., 1998) when the calculation is based on daily values. When using hourly values as input, the the canopy resistance of r_c = 70 s m^{-1} (Allen et al., 1998) changes to 50 s m^{-1} for daytime and 200 s m^{-1} for night-time periods when based on hourly weather data (Allen et al, 2006).

2.3.2 The FAO Penman Monteith equation with daily values

The default value is a combination of the ASCE-model Taastrup and Daisy's calculation of ground heat flux. For other combinations, see Appendix 2.4.

The model calculates an hourly value of equation (2.1) by applying time varying values for $R_{n,s}$ and G (if it varies) while daily average values are applied for all other parameters. $R_{n,s}$ varies because S_i is distributed over the day according to the fraction of extra-terrestrial radiation occurring that particular hour.

The FAO Penman Monteith equation with daily values, including Tmin/Tmax

If T_{min}/T_{max} is specified, the model calculates an hourly value of equation (2.1) by applying time varying values for $R_{n,s}$, G and T, while daily average values are applied for all other parameters. The r_c-value is still 70. This is not entirely identical to Allen et al. (1998).

When applying this reference evapotranspiration, two default settings are specified: (use_wet false) and (r_b 20 [s/m]. Changing the first option from false to true would make the model use the specified r_b -value, which is the boundary layer resistance for a wet surface. In the model, the r_c-value in equation (2.1) is exchanged with r_b. This will lead to a significantly higher potential evapotranspiration.

Different methods for calculation of daily E_r are compared in Figure 2.6, Figure 2.7 and Figure 2.8.

2.3.3 The FAO Penman Monteith equation with hourly values

As for the daily values, the default value is a combination FAO_PM equation with the ASCE-model Taastrup and Daisy's calculation of ground heat flux. For other combinations, see Appendix 2.4. Figure 2.3, Figure 2.4 and Figure 2.5 show comparisons of the new default parameterisation (ASCE with Kjaersgaard parameterisation [Taastrup]) and the standard FAO-parameterisation.

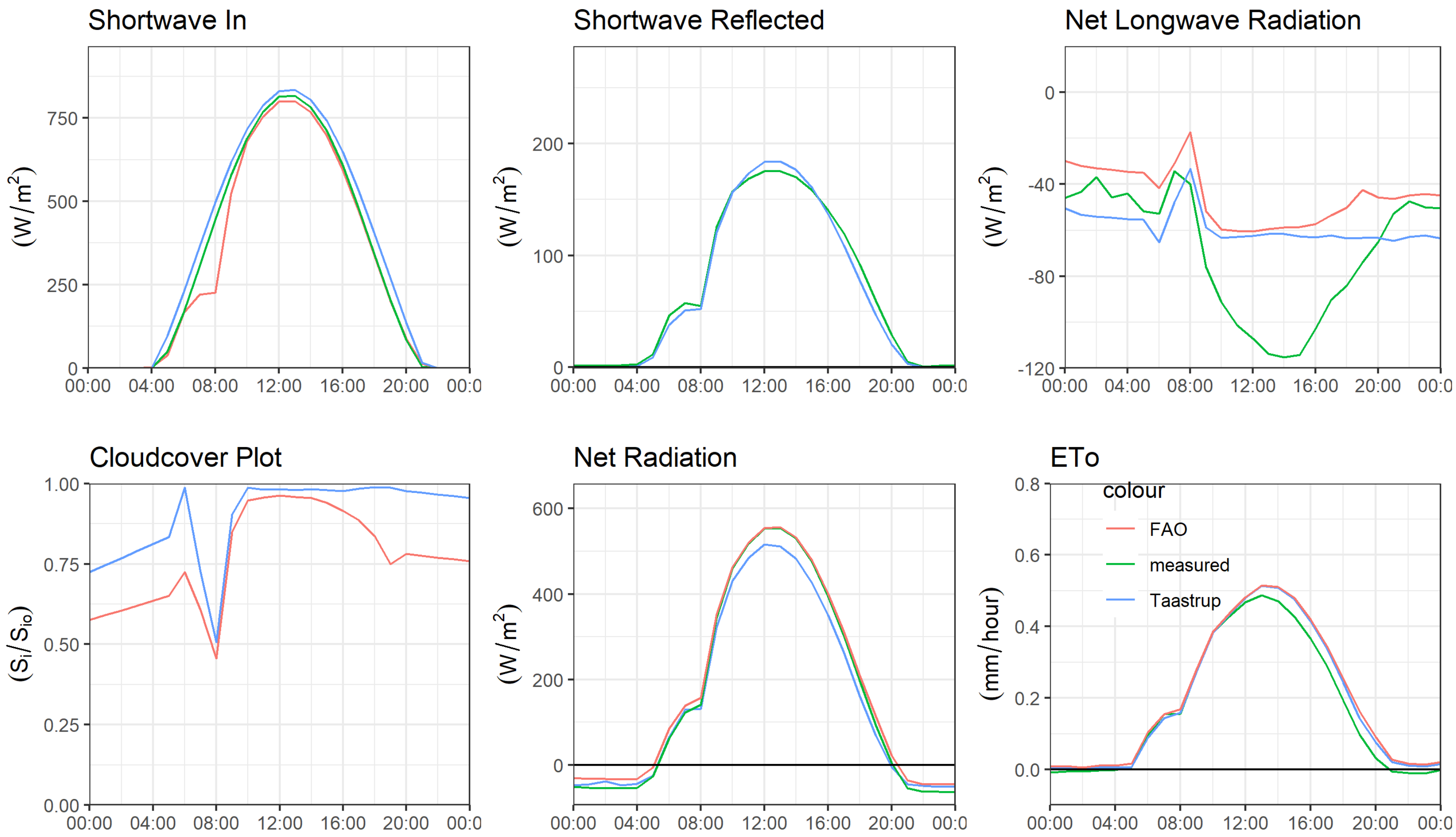
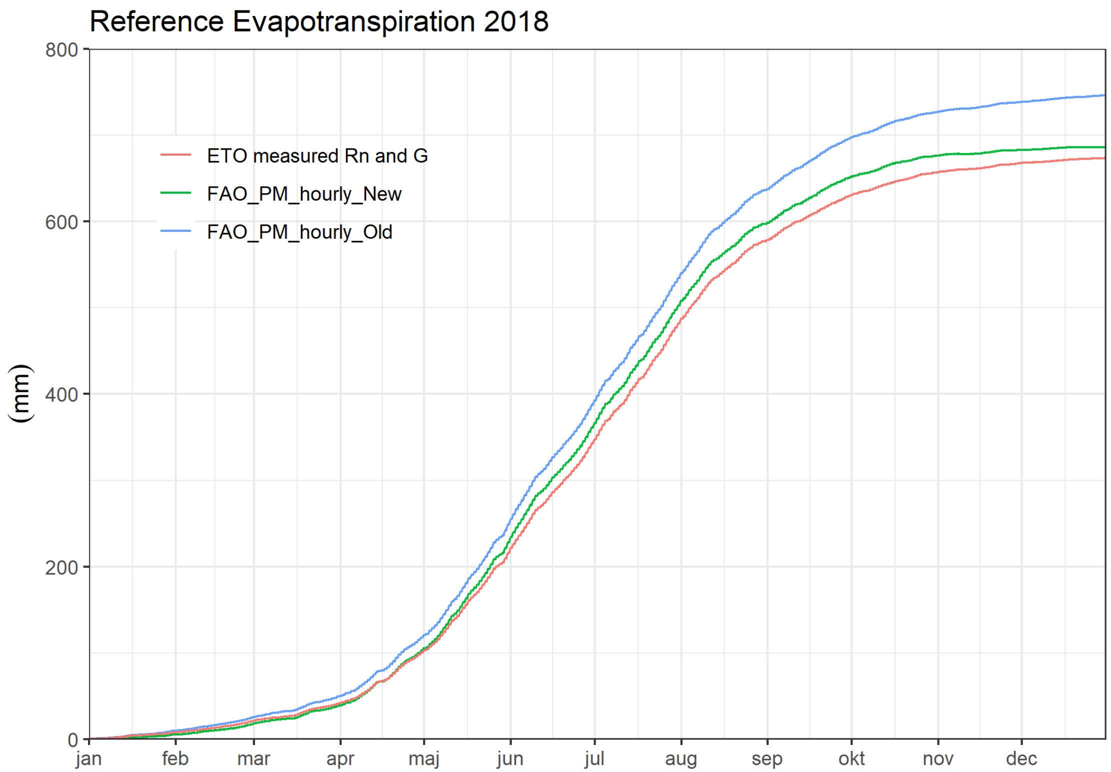
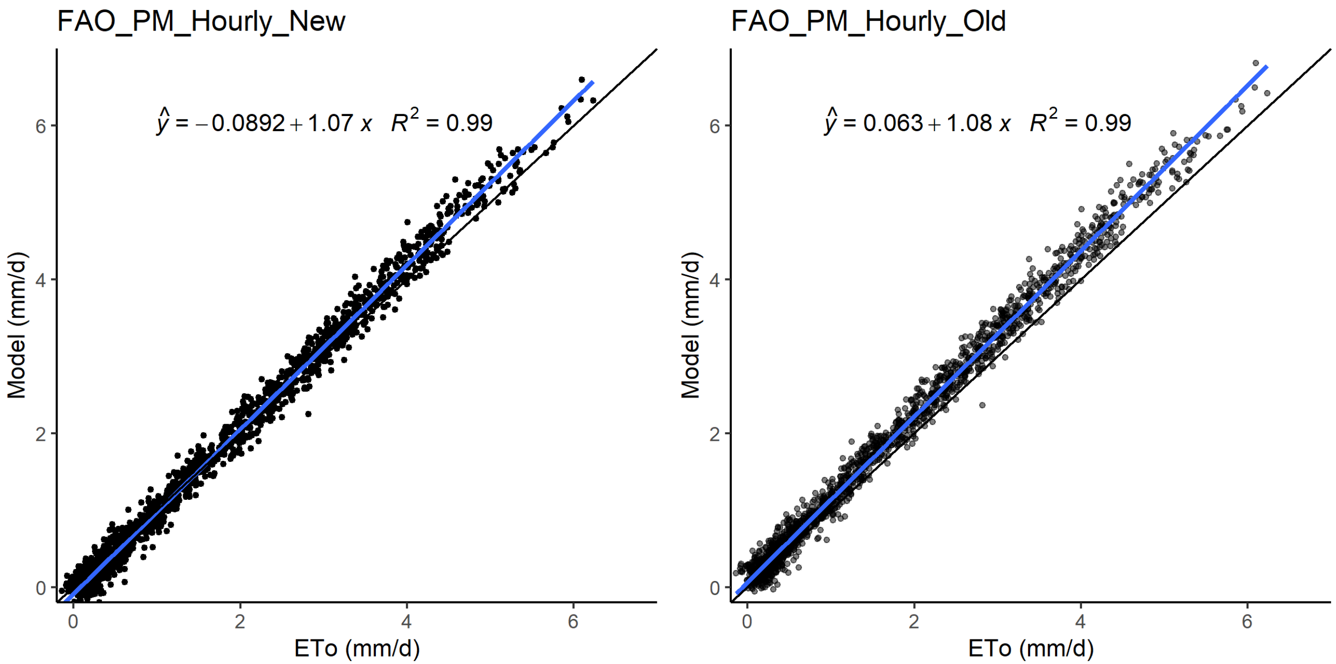


Figure 2.3. Comparison of selected elements of the evapotranspiration calculation. The standard FAO-parameterisation is compared to the "Taastrup"-parameterisation including the ASCE cloudiness function and Kjaersgaard parameterization for a_c and "start/end of day"-criterion and to measurements. Note, that measurements may be influenced by too short grass.



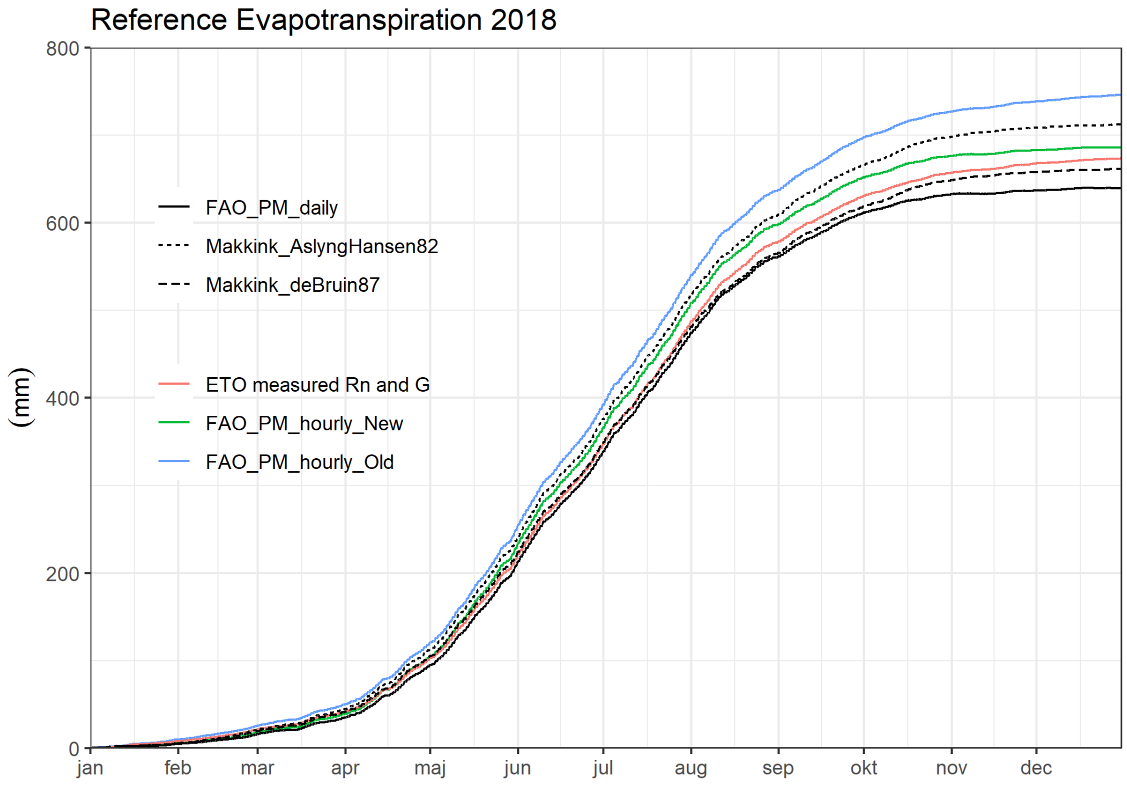
Year	Model	Eto	Diff
2016	FAO_PM_hourly_New	561	7
2016	FAO_PM_hourly_Old	621	67
2016	**Eto measured Rn and G**	**554**	
2017	FAO_PM_hourly_New	508	14
2017	FAO_PM_hourly_Old	569	75
2017	**Eto measured Rn and G**	**494**	
2018	FAO_PM_hourly_New	686	13
2018	FAO_PM_hourly_Old	746	73
2018	**Eto measured Rn and G**	**674**	
2019	FAO_PM_hourly_New	603	3
2019	FAO_PM_hourly_Old	663	64
2019	**Eto measured Rn and G**	**600**	
2020	FAO_PM_hourly_New	643	4
2020	FAO_PM_hourly_Old	702	63
2020	**Eto measured Rn and G**	**639**	

Figure 2.4. The standard FAO-parameterisation is compared to the "Taastrup"-parameterisation including the ASCE cloudiness function and Kjaersgaard parameterization for ac and "start/end of day"-criterion and to calculations based on measurements for reference evapotranspiration in 2018, Taastrup, Denmark. Note, that measurements may be influenced by too short grass.



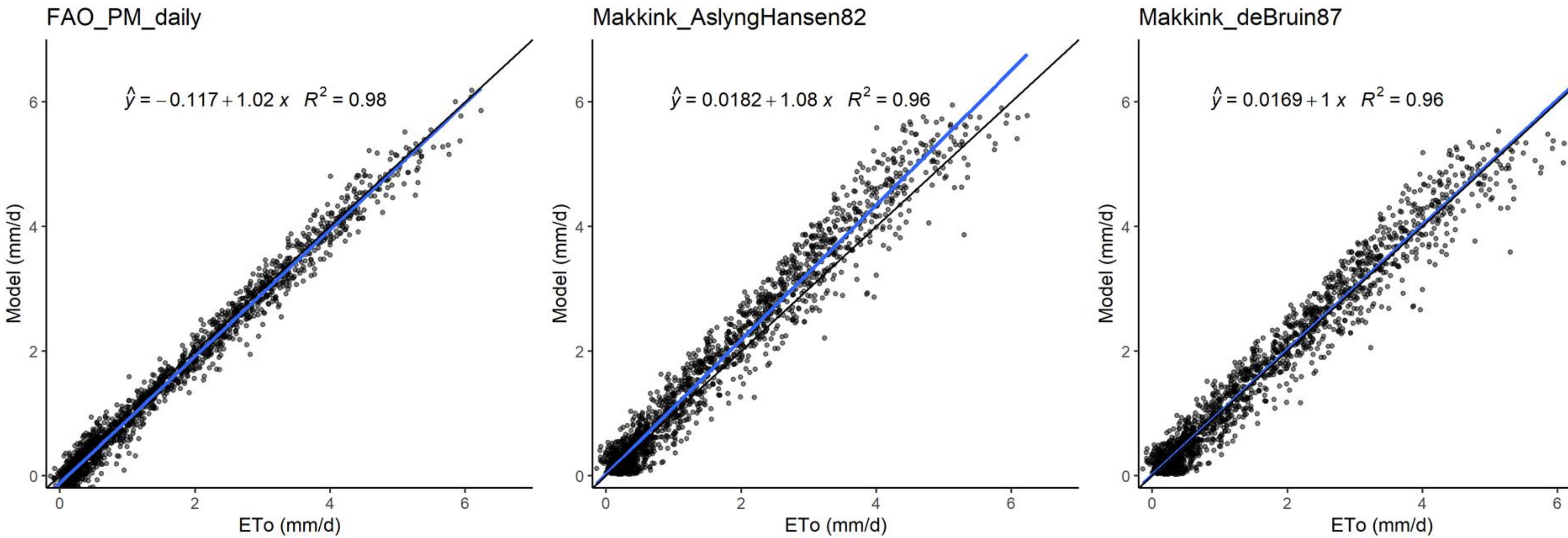
Summary	**Model**	**Eto**	**Diff**
Mean	FAO_PM_hourly_New	600	8
2016-2020	FAO_PM_hourly_Old	660	68
	Eto measured Rn and G	592	

Figure 2.5. The standard FAO-parameterisation is compared to the "Taastrup"-parameterisation including the ASCE cloudiness function and Kjaersgaard parameterization for a_c and "start/end of day"-criterion and to calculations based on measurements for reference evapotranspiration in 2016-20, Taastrup, Denmark. Note, that measurements may be influenced by too short grass.



Year	Model	Eto	Diff
2016	FAO_PM_daily	520	-34
2016	Makkink_AslyngHansen82	622	68
2016	Makkink_deBruin87	578	24
2016	**Eto measured Rn and G**	**554**	
2017	FAO_PM_daily	475	-19
2017	Makkink_AslyngHansen82	569	75
2017	Makkink_deBruin87	529	35
2017	**Eto measured Rn and G**	**494**	
2018	FAO_PM_daily	640	-34
2018	Makkink_AslyngHansen82	713	39
2018	Makkink_deBruin87	662	-12
2018	**Eto measured Rn and G**	**674**	
2019	FAO_PM_daily	561	-38
2019	Makkink_AslyngHansen82	648	48
2019	Makkink_deBruin87	602	2
2019	**Eto measured Rn and G**	**600**	
2020	FAO_PM_daily	597	-42
2020	Makkink_AslyngHansen82	681	42
2020	Makkink_deBruin87	633	-7
2020	**Eto measured Rn and G**	**639**	

Figure 2.6. Comparison between a range of methods for calculation of daily reference evapotranspiration with measurements in Taastrup, Denmark, 2016-2020. Calculated ETref is based on measuren Rn and G. Note, that measurements may be influenced by too short grass.



Summary	Model	Eto	Diff
Mean	FAO_PM_daily	559	-33
2016-2020	Makkink_AslyngHansen82	647	55
	Makkink_deBruin87	601	8
	Eto measured Rn and G	**592**	

Figure 2.7. Comparison between measurements, FAO_PM-daily and two Makkink-parameterisations on daily basis from 2016-2020.

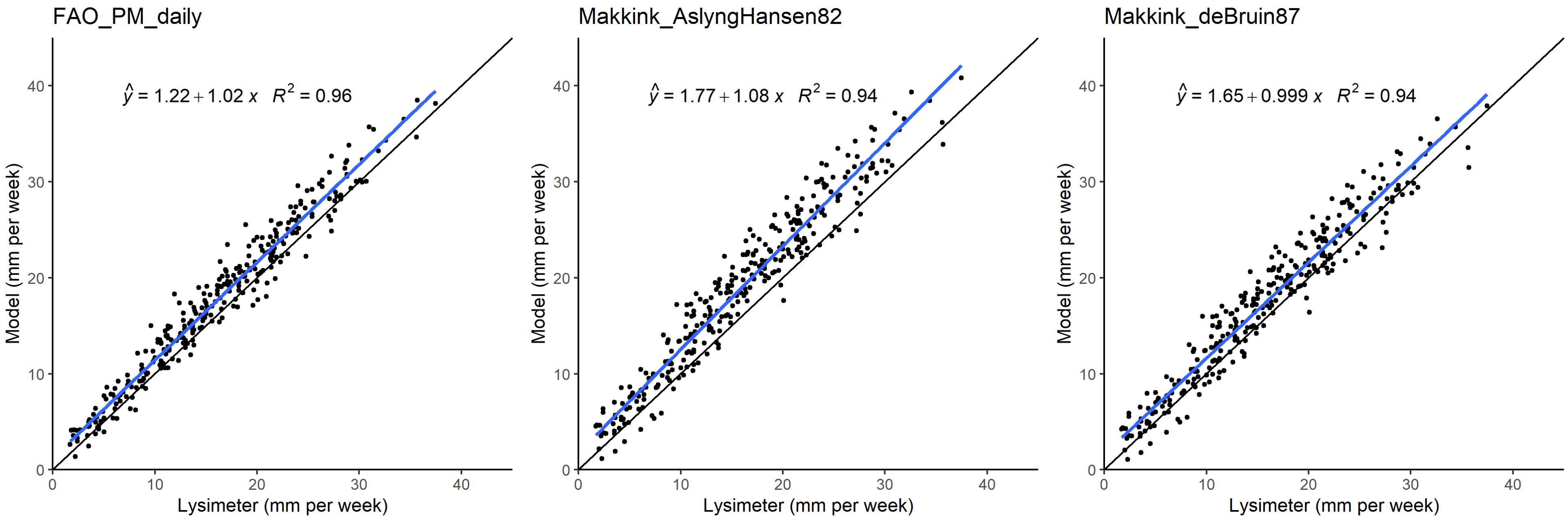


Figure 2.8. Comparison between weekly lysimeter data from mid May to mid October, 1966-1979 and the models FAO_PM_daily, and two Makkink-parameterisations.

2.3.4 The Hargreaves reference evapotranspiration model

The Hargreaves model for estimation of reference evaporation is an empirical model that works with extra-terrestrial radiation, so no radiation has to be measured. The model is described in (Hargreaves and Samani, 1985) and (Hargreaves and Allen, 2003).

The equation is given as

$$E_{r,H} = 0.0023 R_a \cdot conv \cdot (T_{\max} - T_{\min})^{0.5} \cdot (T + 17.8) \tag{2.23}$$

Where

$E_{r,H}$ = Reference evapotranspiration after Hargreaves [mm day^{-1}]

T_{max} = Maximum temperature of the day [°C]

T_{min} = Minimum temperature of the day [°C]

T = Mean temperature of the day [°C]

R_a = Extraterrestrial radiation [MJ m^{-2} day^{-1}]

$conv$= Conversion to evaporation equivalents: 0.4082 [m^2 mm MJ^{-1}]

If R_a is specified as W m^{-2}, an additional conversion factor of (24*60*60/10^6= 0.0864) is required.

The daily value is distributed over the day according to the fraction of extra-terrestrial radiation arriving each hour of the day.

2.3.5 The Makkink reference evapotranspiration with de Bruin parameterisation

The Makkink model can be written as

$$E_{r,M} = \beta_0 + \beta_1 \frac{\Delta}{\Delta + \gamma} \frac{S_i}{\lambda} \tag{2.24}$$

Where β_0 and β_1 are empirical constants calibrated to a certain location and S_i (the global radiation) is in J m^{-2} day^{-1}. Δ, λ and γ are defined according to eq. (2.3), eq. (2.4) and eq. (2.5).

The de Bruin-implementation (de Bruin, 1987) specifies β_0 andβ_1 to 0 [mm day^{-1}] and 0.65 [], respectively.

2.4 Parameter overview

Table 2.2. Related Parameter names in Daisy.

Name and explanation		**Model (in Daisy)**	**Parameter name (Daisy reference manual)**	**Default**	**Default unit**
S_i	Global radiation	weather	*GlobRad*	User input	[W m^{-21}]
T_a	Air temperature	weather	*AirTemp*	User input (hourly or daily)	[°C]
T_{min}	Minimum air temperature	weather	*T_min*	Optional input for daily records	[°C]
T_{max}	Maximum air temperature	weather	*T_max*	Optional input for daily records	[°C]
	(Monthly) Temperature offset.	weather	*TempOffset*	Optional, simple method to change temperatures up or down.	
P	Precipitation	weather	*Precip*	User input (hourly or daily)	[mm h^{-1}]
	Snow fraction of precipitation as f(T)	weather	*snow_fraction*	(0 1) (2 0)	[T] []
	(Monthly) correction factors for precipitation	weather	*PrecipCorrect*	Optional, obsolete with newer methods of precip.correction	[]
	(Monthly) scale factors for precipitation	weather	*PrecipScale*	Optional, used if scaling precipitation from one site to another.	[]
E_r	Reference evapotranspiration	weather	*RefEvap*	Optional input (hourly or daily)	[mm h^{-1}]
e_a	Vapour pressure Relative humidity	weather	*VapPres* *RelHum*	Optional input (hourly or daily) Optional input (hourly or daily)	[Pa] []

Name and explanation		Model (in Daisy)	Parameter name (Daisy reference manual)	Default	Default unit
u_2	Wind speed at 2 m's height	weather	*Wind*	Optional input (hourly or daily)	[m s^{-1}]
	Diffuse radiation	weather	*Diffrad*	By default, calculated in 'difrad'. Can be specified for SSOC-model	[W m^{-2}]
CO_2	Atmospheric CO2-level	weather	*CO2*	Can be specified for SSOC-model	[], fraction of atm. pressure
f_c	Cloudiness factor	weather, bioclimate	*CloudinessIndex*	By default calculated by a cloudiness model. Can be given as input.	[]
a_c	Cloudiness coefficient	cloudiness	*a*	Either 1.35 or 1 depending on choice of cloudiness model	[]
	Different criteria to determine the last hour of cloudiness calculation to be extrapolated and when to start the calculation again.	cloudiness	*min-extraterrestrial_radiation*	0	[W m^{-2}]
		cloudiness	*min_global_radiation*	0 or 25 (diff.submodels)	[W m^{-2}]
		cloudiness	*min_solar_elevation_angle*	0 or 0.174533 (diff.submodels)	[rad]
		cloudiness	*min_radiation_ratio*	0.3	[]
		cloudiness	*min_time_to_sunset*	0	[h]
		cloudiness	*min_time_from_sunrise*	0	[h]
K_t	Parameter for air transparency	ASCE	*Kt*	1	[]

Name and explanation		Model (in Daisy)	Parameter name (Daisy reference manual)	Default	Default unit
G	Soil heat flux	weather, bioclimate	*GHF or ghf*	By default calculated by Daisy, but specific submodels and settings for each FAO-PM parameterisation. Can be given as input.	[W m^{-2}]
φ	Latitude, weather station	weather	*Latitude*	none	[dg North]
L_m	Longitude, weather station	weather	*Longitude*	none	[dg East]
L_z	Time zone, weather station	weather	*TimeZone*	none	[dg East]
z	Elevation, weather station	weather	*Elevation*	none	[m]
z_m	Screenheight	weather	*ScreenHeight*	2 m. Should only be given a different value in case of weather measurements in a field and use of the (non-standard) PM-model	[m]
	Surface type	weather	*Surface*	Default: “reference”, referring to weather station standard of short grass, or “field” for measurements in field, thus using a “non-standard” E_r-calculation.	

Name and explanation		Model (in Daisy)	Parameter name (Daisy reference manual)	Default	Default unit
r_b	Boundary layer resistance for wet surface	FAO_PM FAO_PM_hourly	*rb* *Use_wet*	Default Default: false	[s m^{-1}]
β_0 β_1	Constants in Makkink-equations	deBruin87 AslyngHansen82 Makkink57 Makkink	*Beta_Mo* *Beta_M1*	See each of the implementations for default values	[mm d^{-1}] []
r_b	Boundary layer resistance for wet surface	FAO_PM FAO_PM_hourly	*rb* *Use_wet*	Default Default: false	[s m^{-1}]
J^C_{drydep}	Dry deposition (general)	weather	*NH4DryDep* *NO3DryDep* *Deposition* *DepDry* *DepDryNH4* *PAverage*	Optional input Optional input Or alternatively, total deposition with fractions for dry deposition of total and amm. fraction of this. Average precipitation, required to calculate wet concentrations.	[kg N $ha^{-1}y^{-1}$] [kg N $ha^{-1}y^{-1}$] [kg N ha^{-1}] [] [] mm
c_{wetdep}	Wet deposition, conc. of solute in precipitation	weather	*NH4WetDep* *NO3WetDep*	Optional input Optional input	[ppm = mg $mm^{-1}m^{-2}$]
	Timestep for weather data	weather	*Timestep*		[h]

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Appendices

2.1: Optional implementations of reference evapotranspiration and the PM-models

2.2: Net radiation models implementations

2.3: Bioclimate parameterisations

2.5 References

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