A comparison of some methods to estimate reference evapotranspiration

Validation of DAISY bioclimate module

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Motivation

- The weather station was renovated in Taastrup in 2012-2014. New validated weather file is available with measured net radiation and soil heat flux since 2016.
- Several errors have been discovered in the Daisy bioclimate modules, and new methods to determine net radiation has been implemented recently.

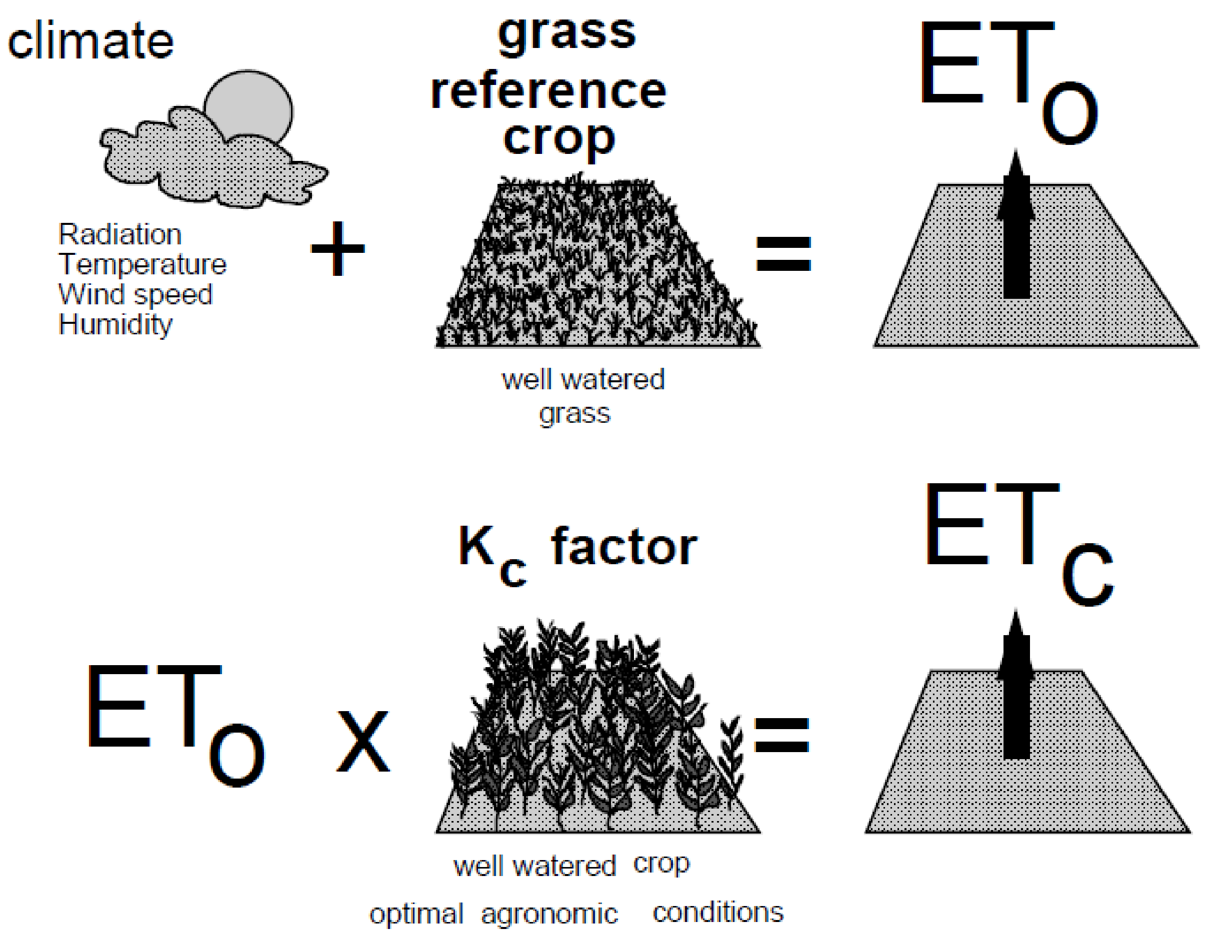
The Taastrup Climate and Water Balance Station

Reference Evapotranspiration (ET_0)

Evapotranspiration (ET) is the sum of water evaporation and transpiration from a surface to the atmosphere.

Evapotranspiration (ET) is most often calculated based on hydrometeorological equations and data from a climatic station with a "none stressed" short grass forming a reference surface. This value is determined by the Reference Evapotranspiration (ET_0).

Potential Evapotranspiration (ET_c) can be calculated directly using the full form Penmann-Montieth equation if data is available. Most often ET_c is estimated based on the Reference Evapotranspiration and a crop factor (K_c)



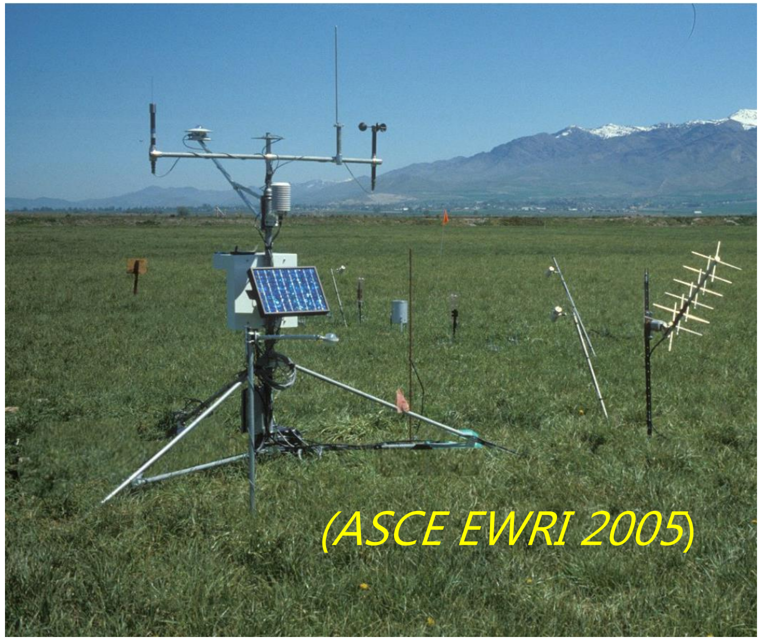
(Allen et al. 1998)

Measurements of ETo and ETc

Indirect

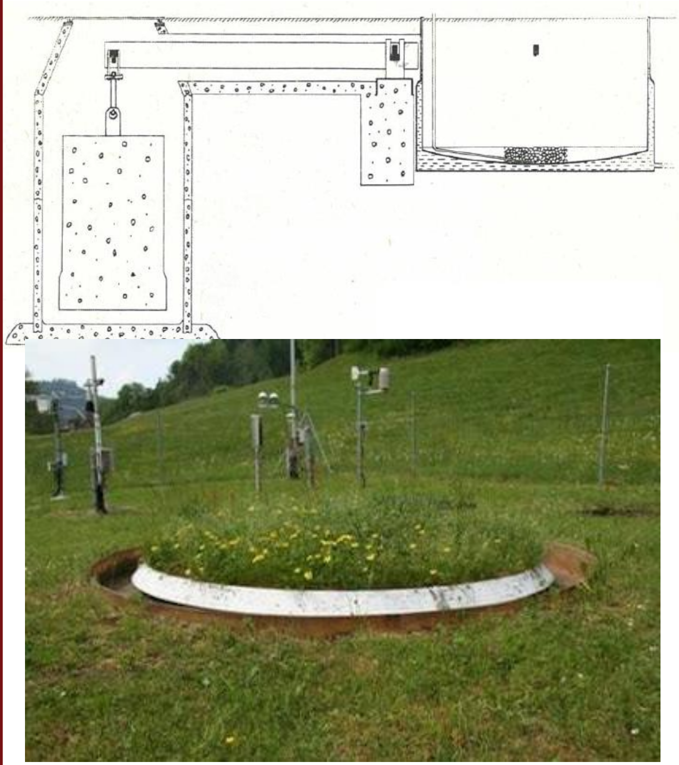
ET_o estimated from weather station data

$Et_c = K_c \times ET_o$



Direct

Lysimeter

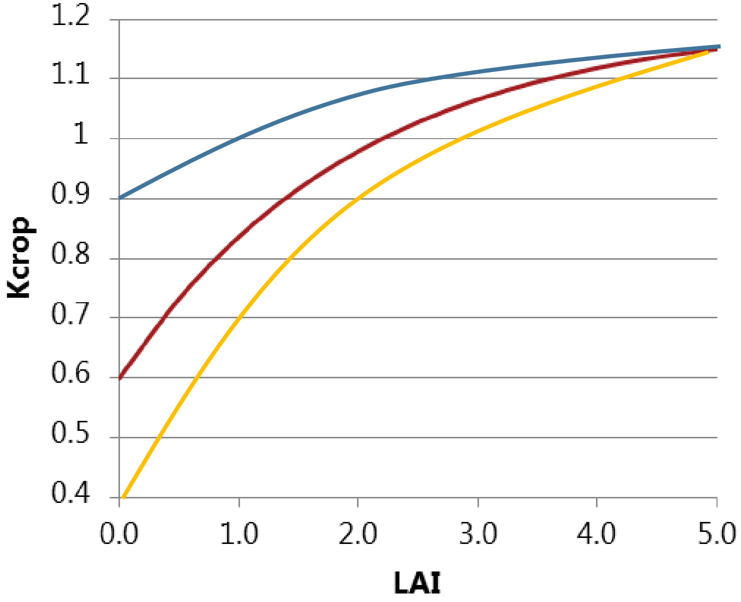


Eddy covariance

DAISY method to estimate Potential Evapotranspiration

$$ET_c = k_c \times ET_0$$
$$= \left(k_{c,soil} e^{-EP_{ext} \times L_{ai}} + k_{c,canopy}\left(1 - e^{-EP_{ext} \times L_{ai}}\right)\right) \times ET_0$$

k_c = crop coefficient
$k_{c,soil}$ = soil coefficient (0.6, Epfactor)
$k_{c,canopy}$ = canopy coefficient (1.2, Epfac)
EP_{ext} = extinction coefficient (0.5, EpExt)



The soil coefficient $k_{c,soil}$ is dependent upon soil moisture conditions (Wet soil ≈1 and Dry soil ≈0.2)

Wet soil

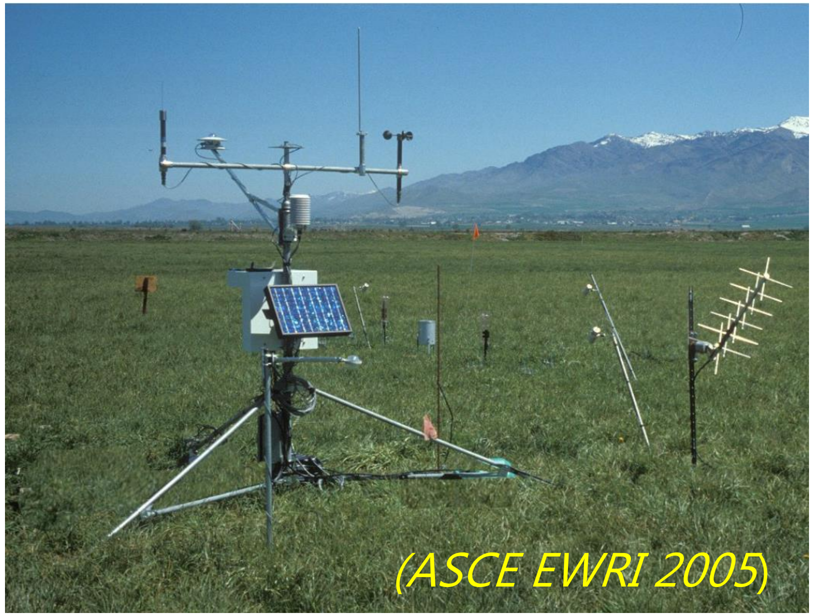
Dry soil

Dry soil + small plants

Dry soil + large plants

FAO reference surface for ET_0

"A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m-1 and an albedo of 0.23." (Allen et al. 1998)



K_C=1; Height 12cm; LAI=2.9

FAO grass surface example
Tall lawn type grass

$K_C \approx$ 0.95-0.99; Height ≈ 6-10cm; LAI ≈ 1.4 – 2.4

Taastrup grass surface
Short lawn type grass cut frequently

Overview of ET models in Daisy

	Field	Reference
Mechanistic	PM	FAO_PM, FAO_PM_hourly
Empirical		Makkink, Hargreaves

- **PM**: Full Penman-Monteith equation for field conditions.
- **FAO_PM, FAO_PM_hourly**: The FAO recommended adjustment of PM with daily or hourly values.
- **Makkink**: An empirical correlation between global radiation, temperature, and ET0. Needs to be calibrated to the individual station, to match the humidity and especially wind conditions. Three such calibrations are provided by default:
  - **Makkink57**: The original calibration by Makkink himself.
  - **AslyngHansen82**: The “traditional” calibration used in Daisy, matching the wind conditions at Taastrup in 1982.
  - **deBruin87**: A slightly newer Dutch calibration, better matching the wind conditions at Taastrup today.
- **Hargreaves**: An empirical correlation between daily min/max temperature, and ET0.

Estimation of daily Reference Evapotranspiration (ET_0)

FAO Penman daily (*Allen et al. 1998*)

$$ET_{0,FAO} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

R_n	net radiation at the crop surface MJ m^{-2} day^{-1}
G	soil heat flux density, MJ m^{-2} day^{-1}
T	mean daily air temperature at 2 m height, °C
u_2	wind speed at 2 m's height, m s^{-1}
e_s	saturation vapour pressure, kPa
e_a	actual vapour pressure, kPa
(e_s-e_a)	saturation vapour pressure deficit, kPa
Δ	slope of the vapour pressure curve, kPa °C^{-1}
γ	psychrometric constant, kPa °C^{-1}

Makkink (*Makkink 1957, Aslyng and Hansen 1982, de bruin 1987*)

$$ET_{0,M} = \beta_0 + \beta_1 \frac{\Delta}{\Delta + \gamma} \frac{S_i}{\lambda}$$

β_0	Constant, Makkink57=-0.12, AslyngHansen82=0, deBruin87= 0, mm d^{-1}
β_1	Constant, Makkink57=0.56, AslyngHansen82=0.7 deBruin87= 0.65
S_i	Global radiation
Δ	slope of the vapour pressure curve, kPa °C^{-1}
γ	psychrometric constant, kPa °C^{-1}

Sensitive to calculation method. Daisy will not accept daily averages of relative humidity in the weather file!

Estimation of hourly Reference Evapotranspiration (ET_0)

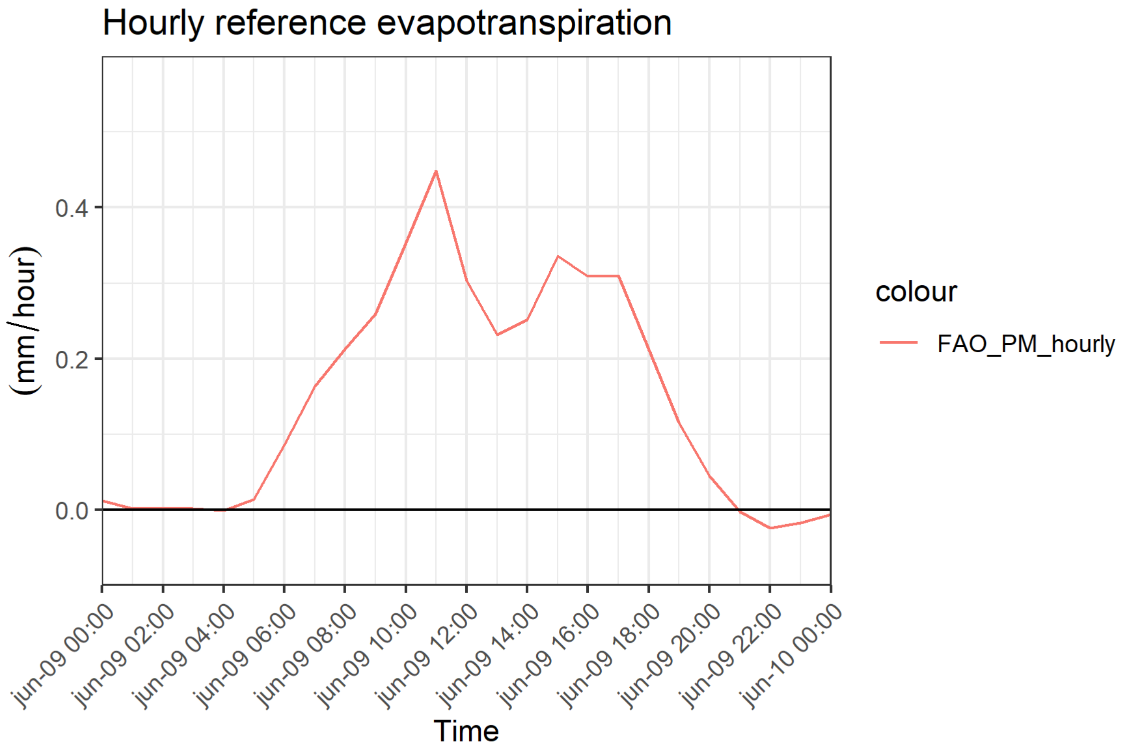
FAO Penman hourly (*Allen et al. 2006*)

$$ET_{0,FAO\_hourly} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}$$

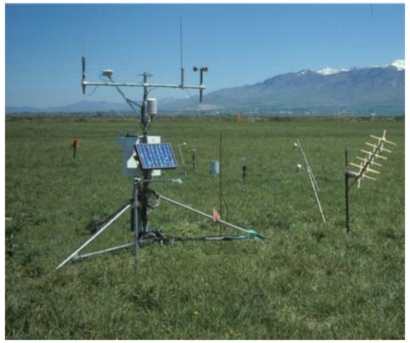
R_n	net radiation at the crop surface MJ m^{-2} day^{-1}
G	soil heat flux density, MJ m^{-2} day^{-1}
T	mean daily air temperature at 2 m height, °C
u_2	wind speed at 2 m's height, m s^{-1}
e_s	saturation vapour pressure, kPa
e_a	actual vapour pressure, kPa
(e_s-e_a)	saturation vapour pressure deficit, kPa
Δ	slope of the vapour pressure curve, kPa $°C^{-1}$
γ	psychrometric constant, kPa $°C^{-1}$

C_n=37
C_d=0.24 (Day-time)
C_d=0.96 (Night-time)

In the hourly form the surface resistance (r_s) is dynamic, using r_s=(50 s m^{-1}) for daytime and r_s=(200 s m^{-1}) as night-time value by changing the C_d coefficient. Default daily uses a constant r_s=(70 s m^{-1})⇔cd=0.34.



Meteorological data requirements



Problem: Most weather station do not provide measurements of R_n and G. Solution use the less precise makkink or the FAO net radiation submodule to estimate R_n and G.

Parameter	Name	Unit	FAO-PM equation	Makkink equation	University station in Taastrup	DMI-station	Low-cost field stations e.g. fieldsense
T	Air temperature	^oC	x	x	x	x	x
e_a	Actual vapour pressure	kPa	x		x	x	x
u_2	Wind speed at 2 m´s height	$m\ s^{-1}$	x		x	x	x
S_i	ShortWave incoming radiation	$W\ m^{-2}$	x	x	x	x	
S_o	ShortWave outgoing radiation	$W\ m^{-2}$	x		x		
L_i	LongWave incoming radiation	$W\ m^{-2}$	x		x		
L_o	LongWave outgoing radiation	$W\ m^{-2}$	x		x		
G	Soil heat flux	$W\ m^{-2}$	x		x		

$$R_n = S_i - S_o + L_i - L_o$$

The FAO net-radiation submodule

Net radiation is calculated using a fixed albedo of 0.23 and net longwave estimated following the FAO parameterization of Brunt 1932

$$R_n = S_i - (\alpha S_i) - L_n \qquad \alpha = 0.23$$

$$L_n = f_c\left(0.34 - 0.14\sqrt{e_a}\right)\sigma T^4$$

$$f_{c,FAO} = 1.35\left(\frac{S_i}{S_{ic}}\right)\text{-}1.35 \qquad \textit{(Allen et al. 1998,Brunt 1932)}$$

Where S_{ic} is clear sky radiation

$$f_{c,Kjærsgaard} = 1.0\left(\frac{S_i}{S_{ic}}\right) \qquad \textit{(Kjærsgaard 2007)}$$

Kjærsgaard et al. 2007 recommended the coefficients 1 and 0 based on long term net radiation measurements from Taastrup

$$G_{day} = 0.1R_n$$
$$G_{nigth} = 0.5R_n$$

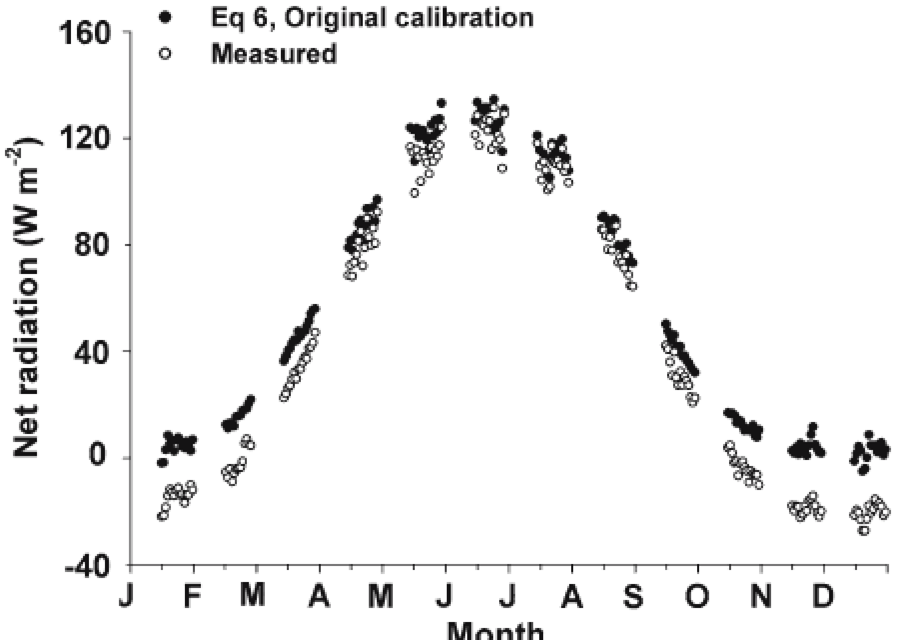
Soil heat flux (*Allen et al. 1998*)

Boundary-Layer Meteorol (2007) 123:417–431
DOI 10.1007/s10546-006-9151-8

ORIGINAL PAPER

Long-term comparisons of net radiation calculation schemes

J. H. Kjaersgaard · R. H. Cuenca · F. L. Plauborg · S. Hansen



Clear sky radiation

FAO standard method suggest a clear sky radiation (S_{ic}) is calculated using exoatmospheric radiation (R_{ext}) and a simple surrogate for the atmospheric air mass and transmissivity. ASCE-EWRI 2005 suggested a new method.

$$S_{ic} = a_s x R_{ext}$$

$$a_{s,FAO} = 0.75 + 2 \times 10^{-5} \times Z$$

(Allen et al. 1998)

$$a_{s,ASCE} = (K_B + K_D)$$

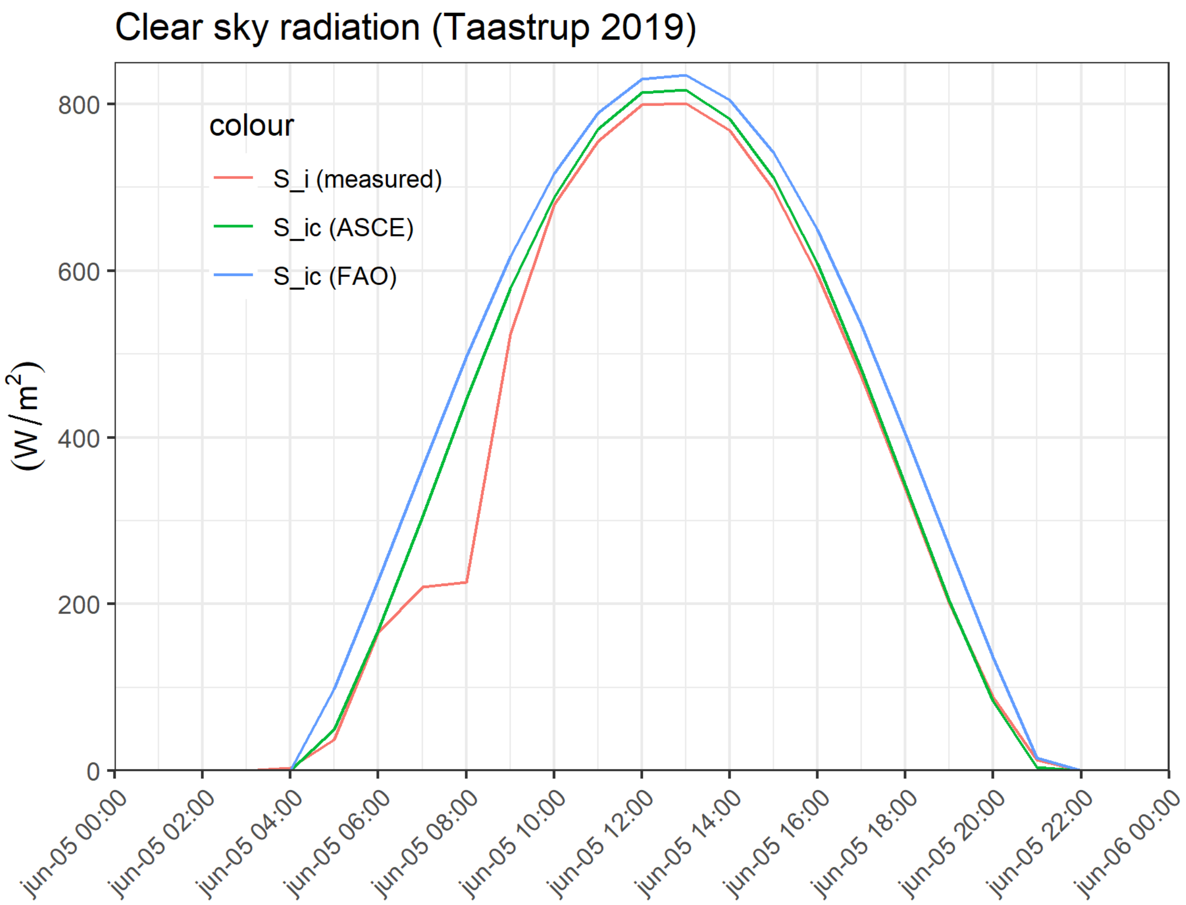
(ASCE-EWRI 2005)

$$K_B = 0.98 \exp\left[\frac{-0.00146 \cdot P_A}{K_t \sin(\theta)} - 0.075\left(\frac{W_P}{\sin(\theta)}\right)^{0.4}\right]$$

$$W_P = 0.14 \cdot e_a \cdot P_A + 2.1$$

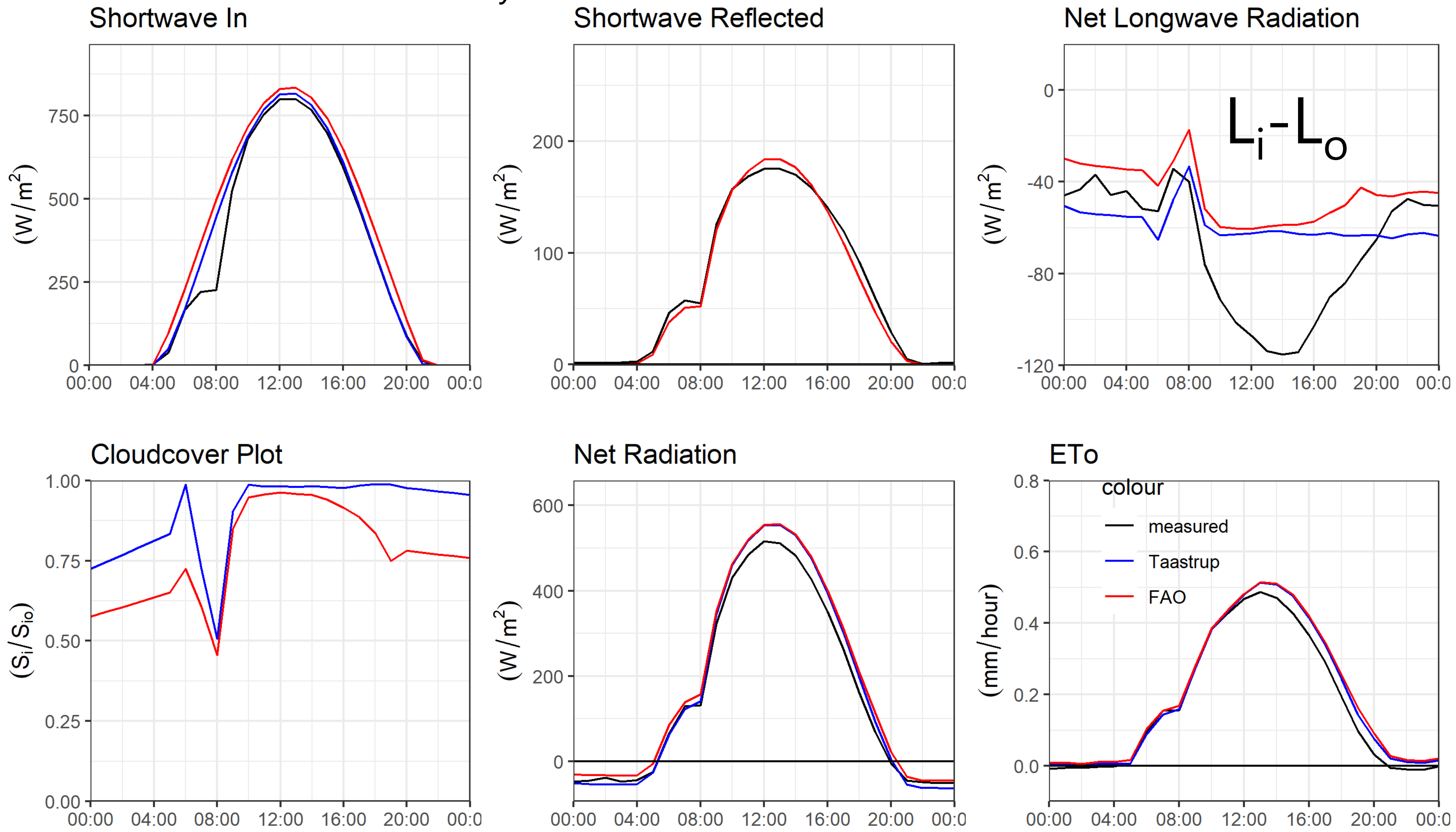
$$K_D = \begin{Bmatrix} 0.35 - 0.36 K_B & \text{for } K_B \geq 0.15 \\ 0.18 + 0.82 K_B & \text{for } K_B < 0.15 \end{Bmatrix}$$

P_a=Air pressure (kPa),Θ=solar angle (radians), Kt air clarity constant. (1.0 [ ] Default)



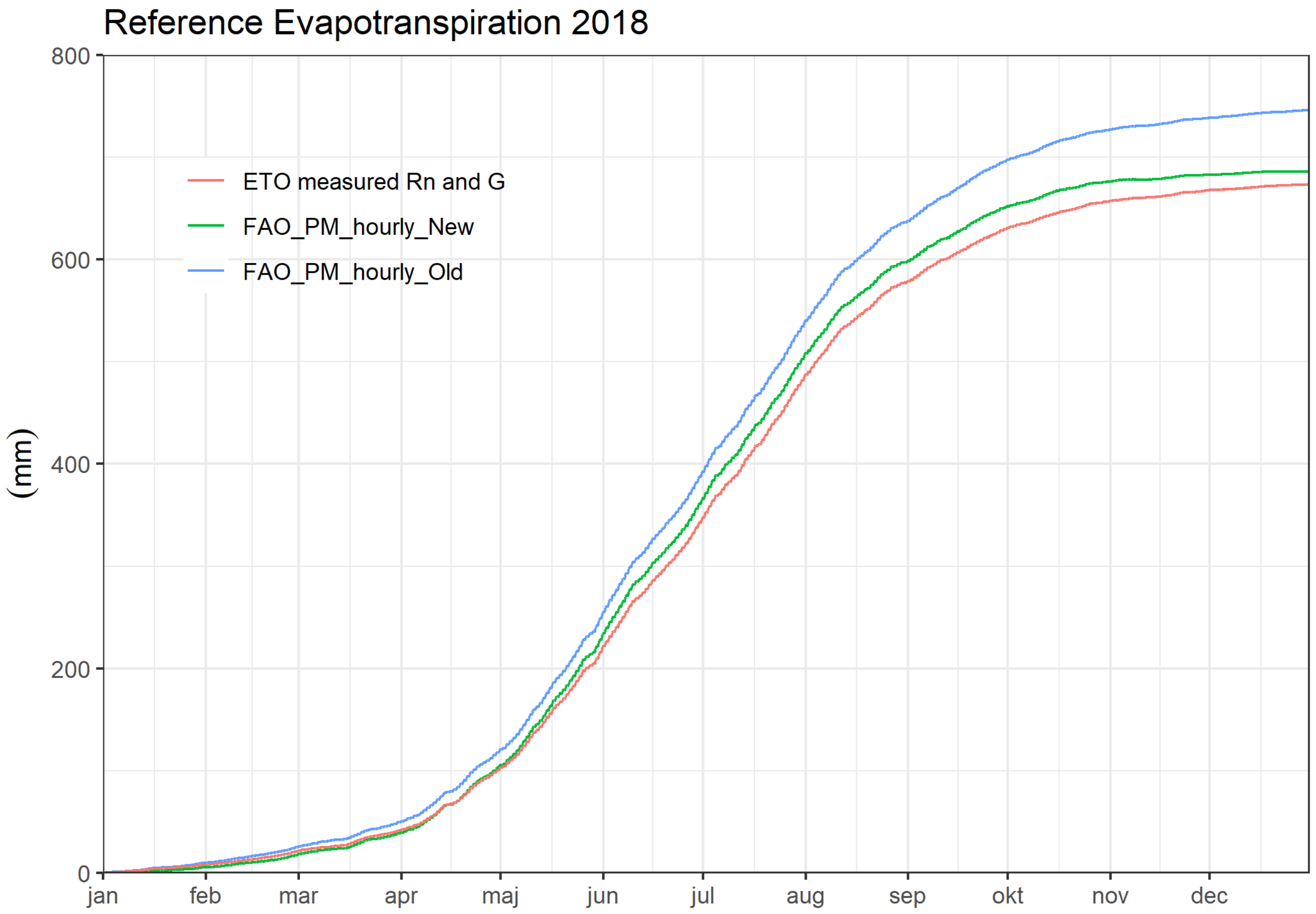
New net radiation sub-model in DAISY (August 2021)

The “Taastrup” has replaced the original FAO model as default for hourly time steps using “Kjærsgaard” cloudiness function and the “ASCE-EWRI” clear sky model.



ET_o calculated using net radiation sub-models (Hourly)

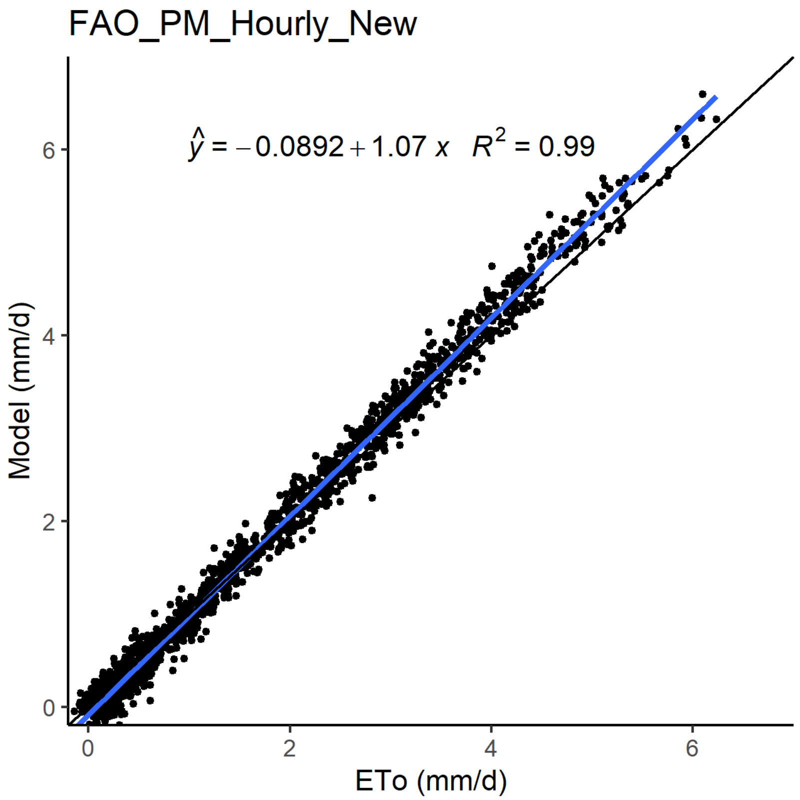
ETo=FAO_PM_hourly calculated using measured Rn and G

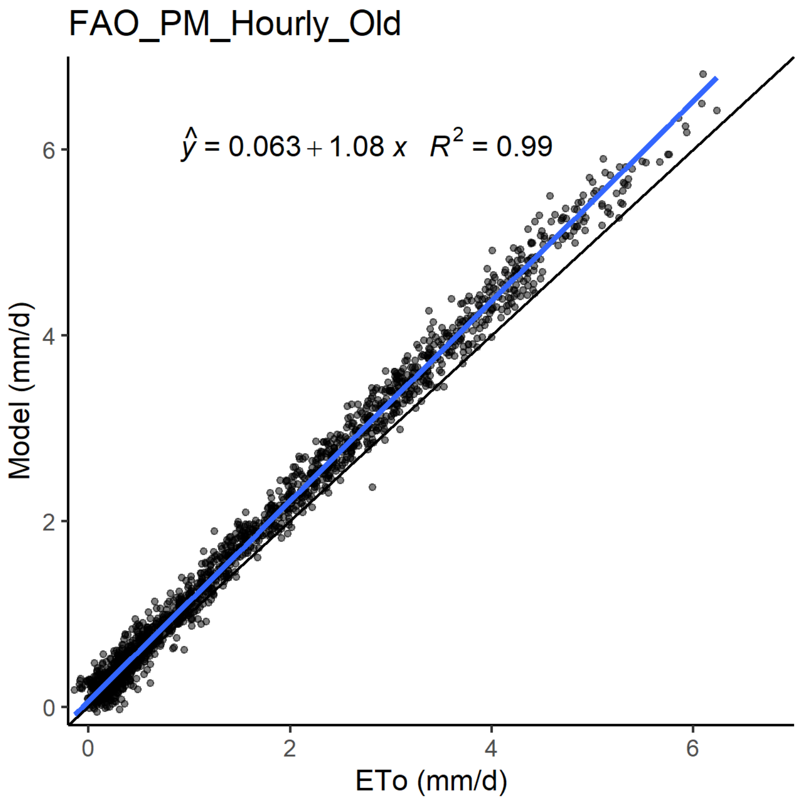


Year	Model	Eto	Diff
2016	FAO_PM_hourly_New	561	7
2016	FAO_PM_hourly_Old	621	67
2016	**Eto measured Rn and G**	**554**	
2017	FAO_PM_hourly_New	508	14
2017	FAO_PM_hourly_Old	569	75
2017	**Eto measured Rn and G**	**494**	
2018	FAO_PM_hourly_New	686	13
2018	FAO_PM_hourly_Old	746	73
2018	**Eto measured Rn 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**	

ET_o calculated using net radiation sub-models (Hourly data)

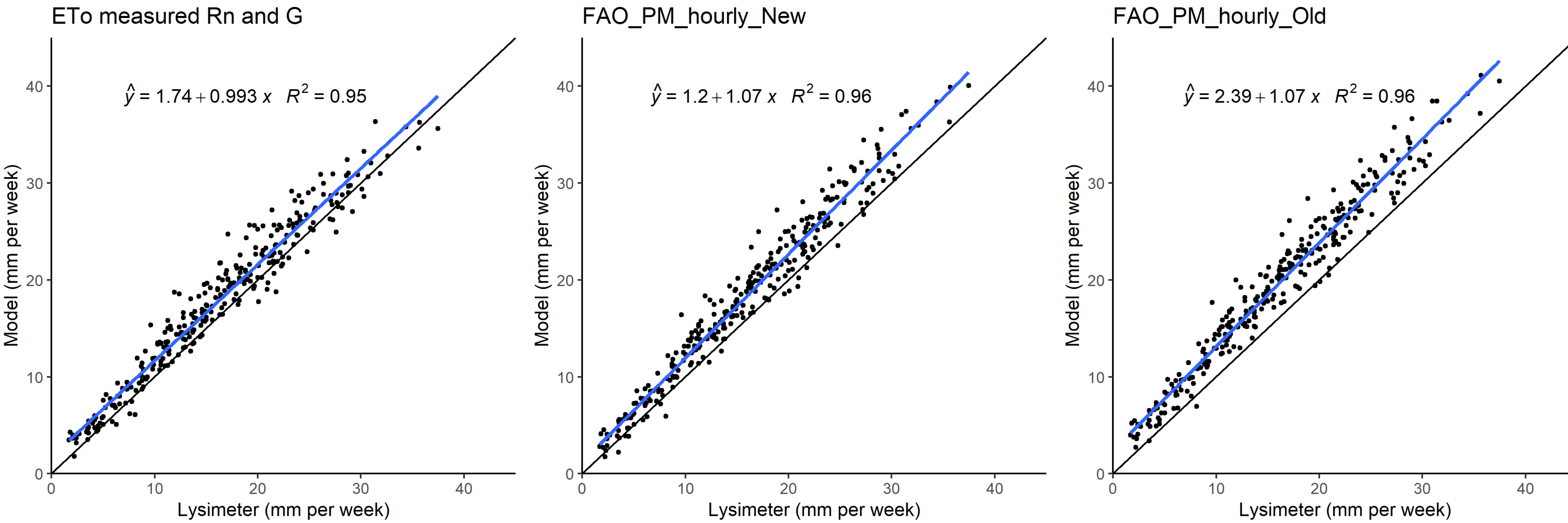
Summary	Model	Eto	Diff
Mean	FAO_PM_hourly_New	600	8
2016-2020	FAO_PM_hourly_Old	660	68
	Eto measured Rn and G	592	



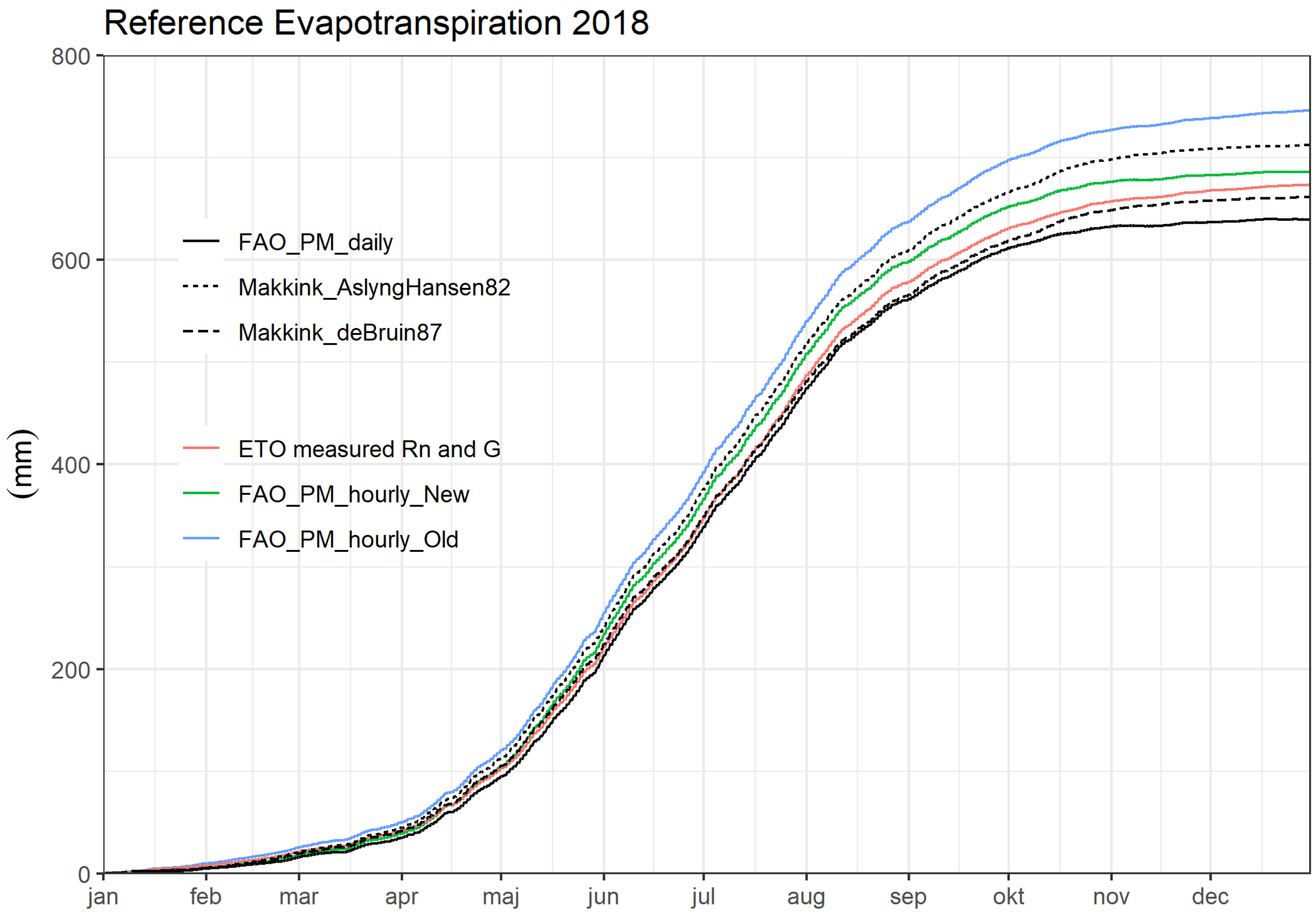


ETo hourly validation to Lysimeter data (1966-1979)

Weekly data from “summer” months only mid May to mid October



ET_o calculated using daily weather data

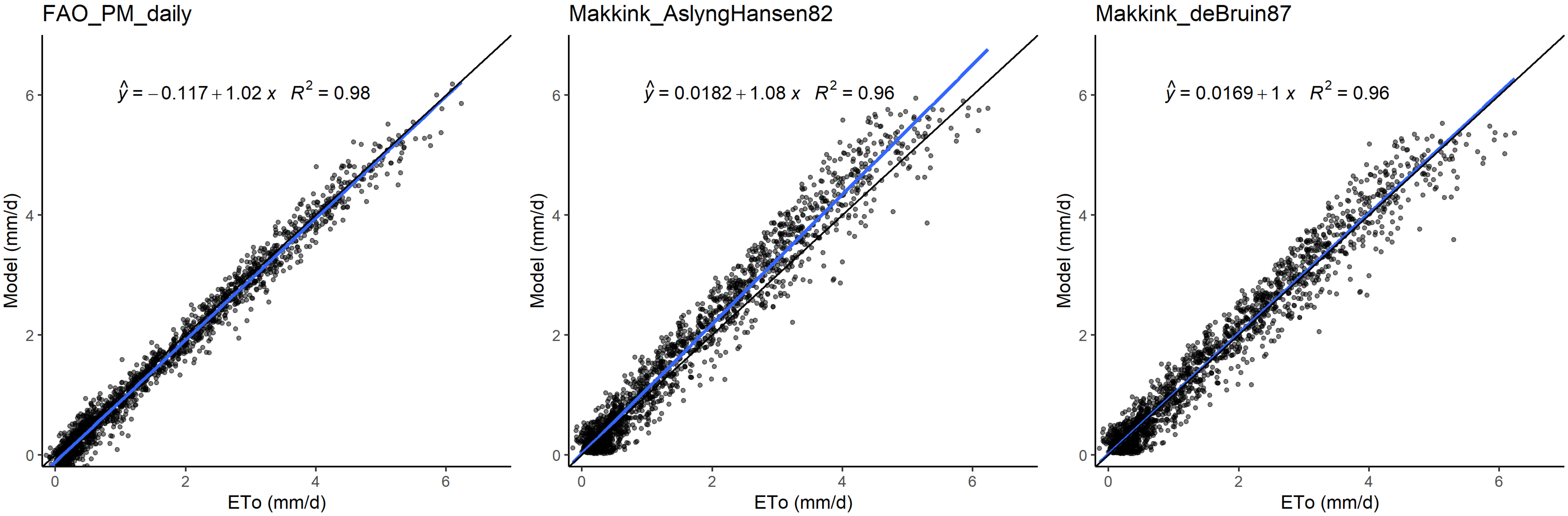


ETo=FAO_PM_hourly calculated using measured Rn and G

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**	

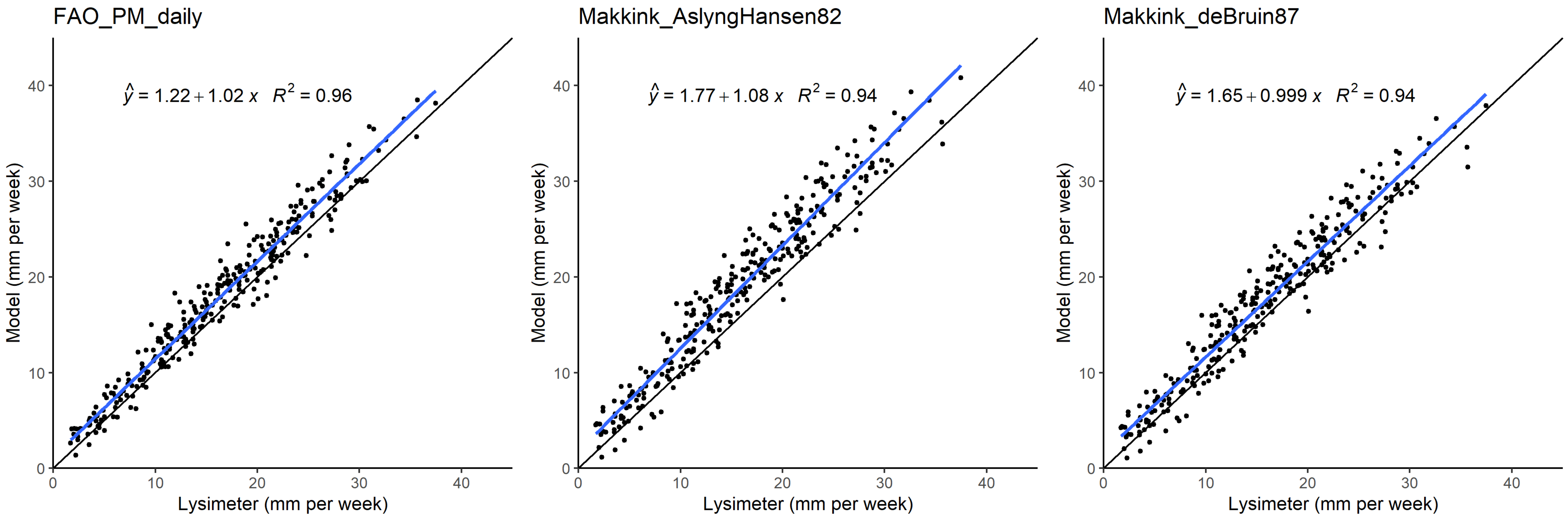
ET_o calculated using daily data

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**	



ET_o daily validation to Lysimeter data (1966-1979)

Weekly data from “summer” months only mid May to mid October



Recommendations

- If you have measured wind, vapour pressure and global radiation, the default daisy setup will use the FAO models for Daily or hourly time steps.
- If possible, consider using hourly time steps. The new FAO penman hourly model implemented with the Taastrup net radiation sub-model closely match ETo determined with measured Rn and G.
- If you lack vapour pressure or wind, please consider whether your weather station is located similarly to our weather station, especially with respect to wind. Also, your ET0 may change, as we now use a different calibration compared to earlier by default.
- deBruin87 seems to come closest to the "modern" Taastrup conditions and is now default in Daisy if your weather data lacks Wind and Vapour data.

New DMI data download script available

https://daisy.ku.dk/dmi-weather-data/

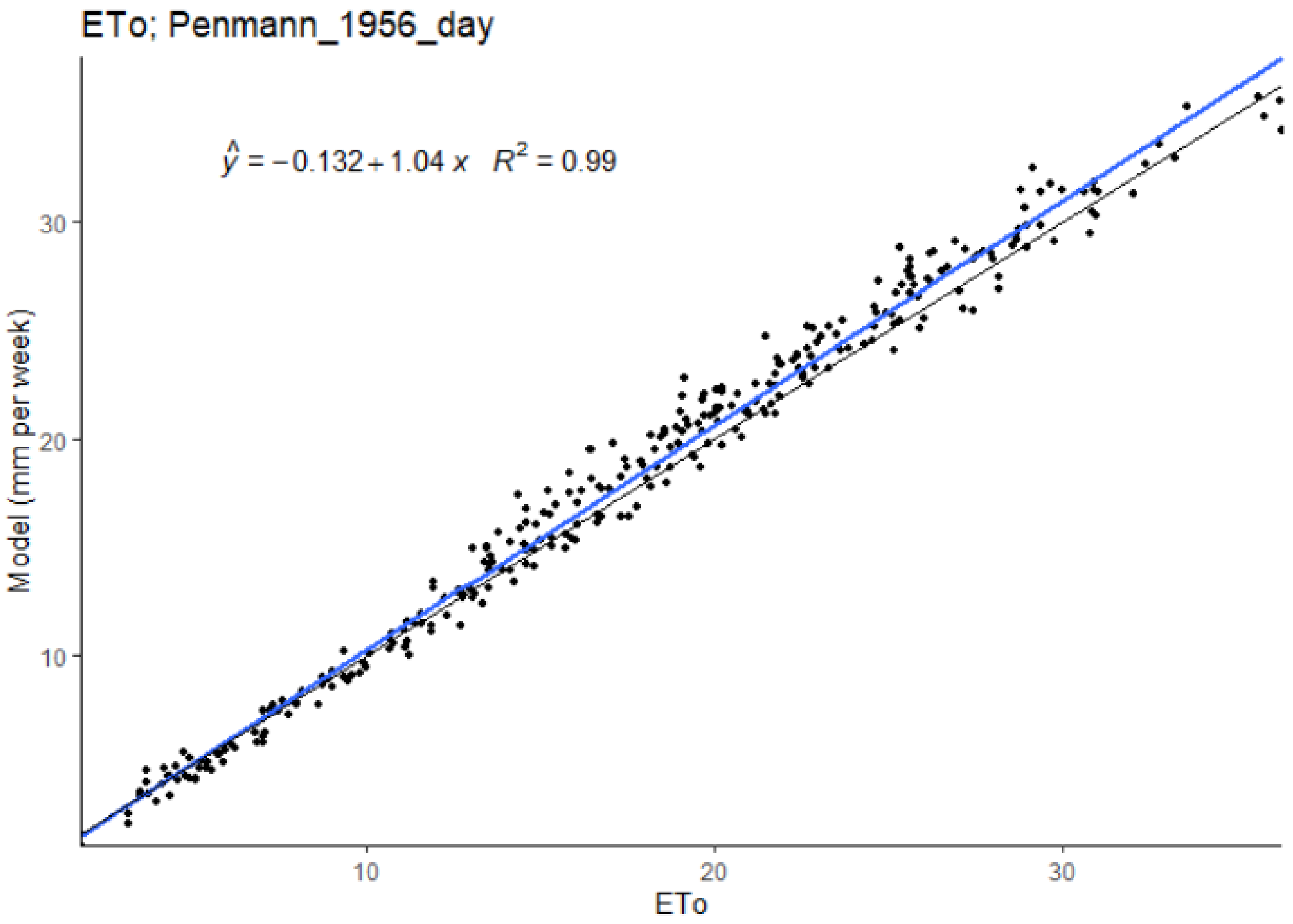
- Per Abrahamsen has made a new python script available online for download of DMI data. DMI has made weather station data as well as interpolated grid data available through an API.
- The script is based on code copied from Lasse Regin's DMI Open Data API project on GitHub.
- It is now possible to estimate FAO_PM_hourly ETo from all locations in Denmark using Daisy. Be careful! The wind is given in 10 meters height. It needs to be vertical displaced, and locale shelter effects should be modelled.

Slide to Carsten

ETo calculated using
FAO_Penman_hourly with measured Rn
And G is similar to the old FAO
Penman 1956 equation based on daily
measurements

$$E_{p,Græs} = \frac{s\left(R_n - G\right)}{\lambda\left(s+\gamma\right)} + \frac{\gamma f\left(u\right)\left(e_s\left(T_a\right) - e_a\right)}{s+\gamma}$$

$$f\left(u\right) = 0.00263\left(0.5 + 0.54u\right)$$



Old validation experiments

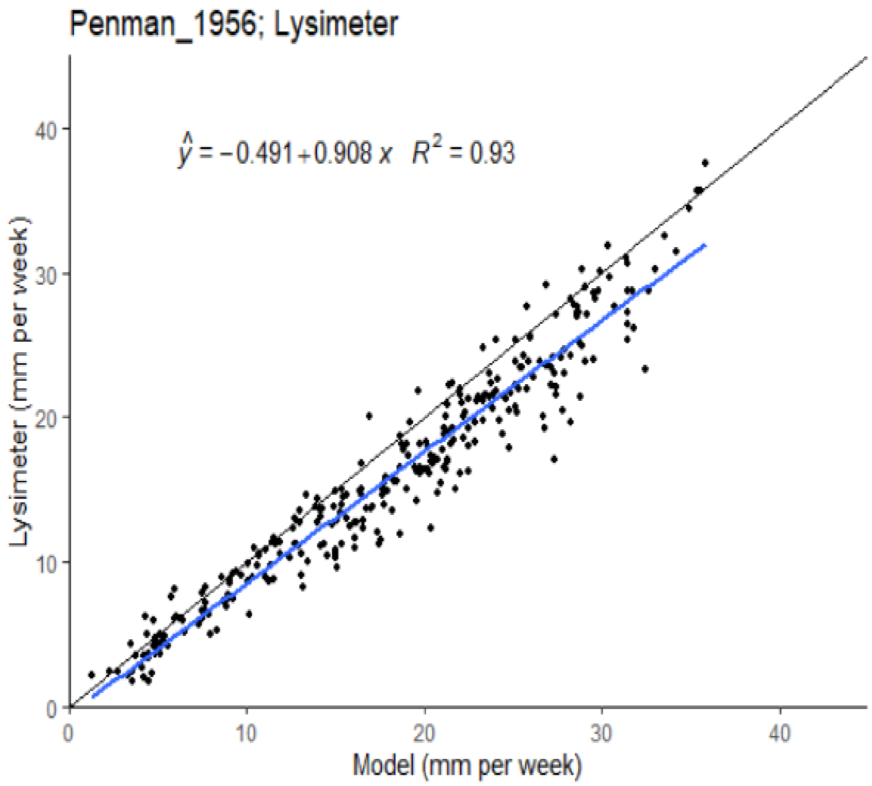
Penman 1956,
using daily data

$$E_{p,Græs} = \frac{s(R_n - G)}{\lambda(s+\gamma)} + \frac{\gamma f(u)(e_s(T_a) - e_a)}{s+\gamma}$$

$$f(u) = 0.00263(0.5 + 0.54u)$$

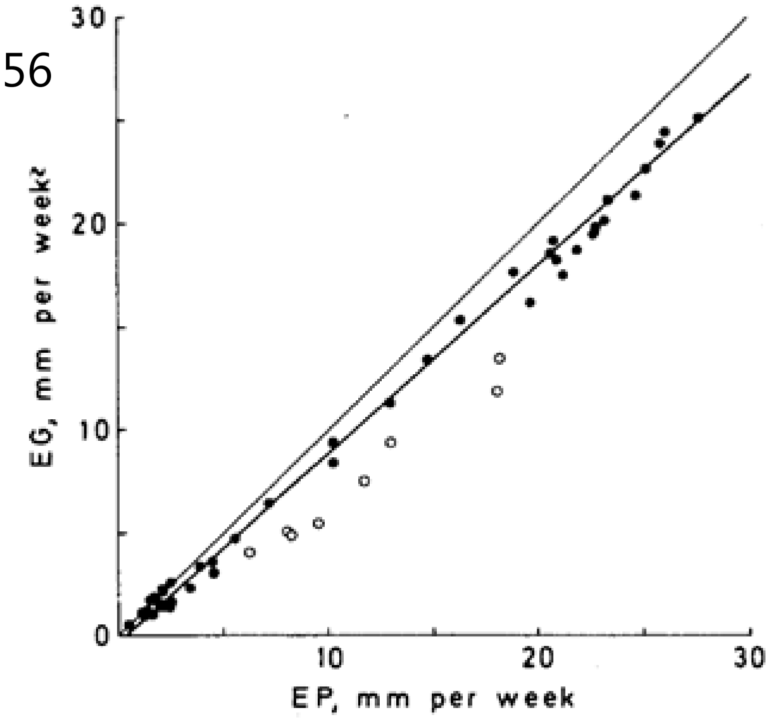
Fig. 6. Relation between calculated potential evapotranspiration (EP) and measured evapotranspiration from grass-covered, weighable evapotranspirometers (EG). 1. to 52. week. Average of the years 1966-1978. The relationship stated is exclusive 11. to 18. week, shown by open dots.
EG = −0.58 + 0.921 EP (r^2 = 0.938).

New calculations using old data



Kristensen 1978

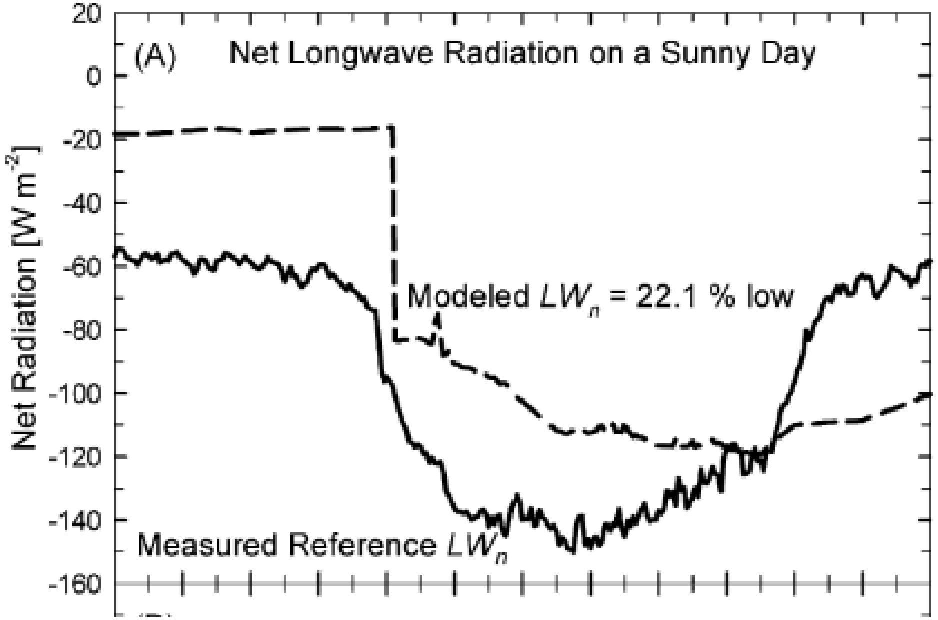
Penman 1956



Blonquist longwave problem in the FAO Rn sub-model

Direct solar heating of the reference surface leads to increase in the longwave emitted radiation during clear days. This process is not captured by Brunt. Might be partly compensated by the FAO soil heat flux estimation method

Logan, Utah, USA



We see the same in Taastrup