Modelling energy balance in the wheat crop model *SiriusQuality*2: Evapotranspiration and canopy and soil temperature calculations

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This document describes the equations used in the implementation of the wheat simulation model *SiriusQuality* (Martre et al 2006) originally described by Jamieson and colleagues (Brooking et al 1995; Jamieson et al 1995b; Jamieson et al 1995a; Jamieson et al 1998b). The Annex includes a list of all the symbols used in this document and a diagram showing the relationships between the sub-models of the energy balance and canopy and soil temperature model. *SiriusQuality*2 is developed in the C# language (.Net framework 4.5) using the development environment Microsoft Visual Studio. The energy balance is available as an independent component.

Contents

1. General theory

The energy balance of the crop involves the following components (Allen et al 1998b; Thornley and Johnson 2000):

1. The evapotranspiration rate
2. The heat transfer between the canopy and the air or sensible heat flux
3. The soil heat flux into the ground
4. The heat storage by the canopy
5. and metabolic processes of photosynthesis and respiration

Of these, the last two are generally negligible and are usually ignored.
The energy available to the crop (φ , kg m^{-2} d^{-1}) is:

$$\phi = R_{\mathrm{N}} - G \quad (1)$$

where R_N (g m^{-2} d^{-1}) is the net radiation in equivalent evaporation, and G (g m^{-2} d^{-1}) is the soil heat flux in equivalent evaporation. Neglecting components 4 and 5 above, the energy balance for the crop can be written:

$$\phi = H + E_{\mathrm{t}} \quad (2)$$

where H (g m^{-2} d^{-1}) is the sensible heat flux and E_t (g m^{-2} d^{-1} equivalent to 10^{-3} mm d^{-1}) is the actual transpiration rate. H can be written in terms of the diffusion equation:

$$H = \frac{\rho c_{\mathrm{p}}(T_{\mathrm{c}} - T_{\mathrm{a}})g_{\mathrm{a}}}{\lambda} \quad (3)$$

where ρ (g m^{-3}) is the density of dry air, C_P (MJ g^{-1} $°C^{-1}$) is the specific heat capacity of dry air at constant pressure, T_c is the canopy temperature (°C), T_a is the air temperature (°C), g_a (m d^{-1}) is the boundary layer conductance for heat, and λ (MJ g^{-1}) is the latent heat of vaporization of water at 20°C. Hence, the canopy temperature is given by:

$$T_{\mathrm{c}} = T_{\mathrm{a}} + \frac{R_{\mathrm{N}} - G - E_{\mathrm{t}}}{\frac{\rho c_{\mathrm{P}} g_{\mathrm{a}}}{\lambda}} \quad (4)$$

Here follows a description of the energy balance and the calculation of canopy temperature in the crop wheat model *SiriusQuality*2. In order to help not only model users, but also model developers to understand *SiriusQuality*2 energy balance and canopy temperature models implementation, the structure of the document mimics the structure of software implementation. Each paragraph is named according to the software code names and includes reference to the relevant software code. Underlined words are links to the related equations in this document.

2. Canopy temperature

Equation (4) is implemented in *SiriusQuality*2 as:

$$T_{\mathrm{c}} = T_{\mathrm{a}} + \frac{CropHeatFlux}{10^3 \times \frac{\rho\, c_{\mathrm{P}}\, Conductance}{\lambda}} \tag{5}$$

where the factor 10^3 converts kg in g, *CropHeatFlux* is the crop heat flux, *Conductance* is the boundary layer conductance (click on the function name to see the related equations).

3. Crop heat flux

Combining equations (1) and (2) gives (Penman 1948; Allen et al 1998a; Thornley and Johnson 2000):

$$H = R_{\mathrm{N}} - G - E_{\mathrm{t}} \tag{6}$$

where R_N (g m^{-2} d^{-1}) is the net radiation in equivalent evaporation, G (g m^{-2} d^{-1}) is the soil heat flux, and E_t (g m^{-2} d^{-1}) is the transpiration rate.

4. Net radiation in equivalent evaporation

R_{N} at the surface of the canopy is calculated following Allen et al. (1998) and is given by the difference between incoming and outgoing radiation of both short (N_{sr}, MJ m^{-2} d^{-1}) and long wavelength (N_{olr}, MJ m^{-2} d^{-1}) radiation. R_{N} is given in equivalent evaporation (g m^{-2} d^{-1}) by dividing by λ and multiplying by 10^3 to convert from kg to g:

$$R_{\mathrm{N}} = 10^3 \times \frac{N_{\mathrm{sr}} - N_{\mathrm{olr}}}{\lambda} \tag{7}$$

where N_{sr} is given by:

$$N_{\mathrm{sr}} = (1 - r) R_{\mathrm{S}} \tag{8}$$

where r (dimensionless) is the albedo or canopy reflection coefficient and R_{S} (MJ m^{-2} d^{-1}) is the measured solar radiation. N_{olr} is given by:

$$N_{\mathrm{olr}} = \sigma \times f(Ta_{\mathrm{K}}) \times f_{\mathrm{c}} \times f_{\mathrm{s}} \tag{9}$$

where σ (MJ k^4 m^{-2} d^{-1}) is the Stefan-Boltzmann constant and $f(Ta_{\mathrm{K}})$ (K^4) is a function of the absolute temperature:

$$f(Ta_{\mathrm{K}}) = \frac{(T_{\mathrm{min,K}})^4 + (T_{\mathrm{max,K}})^4}{2} \tag{10}$$

where $T_{\mathrm{min,K}}$ (K) and $T_{\mathrm{max,K}}$ (K) are the minimum and maximum absolute temperature. f_c (dimensionless) is a cloud cover factor calculated as:

$$f_c = 1.35 \times \frac{R_{\mathrm{S}}}{R_{\mathrm{SO}}} - 0.35 \tag{11}$$

where R_{SO} (MJ m^{-2} d^{-1}) is the clear sky solar radiation calculated as:

$$R_{\mathrm{SO}} = (0.75 + 2 \times 10^{-5} \times A) \times R_{\mathrm{a}} \tag{12}$$

where R_{a} (MJ m^{-2} d^{-1}) is the extraterrestrial solar radiation, A (m above sea level) is the elevation. Finally, f_{s} (dimensionless) is a surface emissivity factor calculated as:

$$f_{\mathrm{s}} = 0.34 - 0.14 \times \sqrt{\frac{\mathrm{VP}}{10}} \tag{13}$$

where VP (kPa) is the air vapor pressure. VP is divided by 10 to convert it in hPa.

5. Soil heat flux

The available energy in the soil (G, g m^{-2} d^{-1}), given by:

$$G = \tau R_{\mathrm{N}} - E_{\mathrm{soil}} \tag{14}$$

where τ is the fraction of radiation intercepted by the crop (Monsi and Saeki 1953):

$$\tau = e^{(-K_L \mathrm{LAI})} \tag{15}$$

Where K_{L} (m^{-2} (ground) m^{-2} (leaf)) is the light extinction coefficient and LAI (m^{-2} (leaf) m^{-2} (ground)) is the leaf area index. E_{soil} (g m^{-2} d^{-1}) is the soil evaporation (see Soil Evaporation,

6. Soil evaporation

Starting from a soil at field capacity, soil evaporation (E_{soil}, g m^{-2} d^{-1}) is assumed to be energy limited during the first phase of evaporation and diffusion limited thereafter (Ritchie 1972). Hence, the soil evaporation model consider these two processes taking the minimum between the energy limited evaporation (PtSoil) and the diffused limited evaporation (SlosI) (Jamieson et al 1995b):

$$E_{\mathrm{soil}} = \min(Slosl, PtSoil) \quad (16)$$

6.1 Energy limited evaporation: PtSoil

Evaporation from the soil in the energy-limited stage (*PtSoil*, g m^{-2} d^{-1}) is given by (Tanner and Jury 1976):

$$PtSoil = \frac{E_{\mathrm{p,PT}}}{\alpha} \alpha_{\mathrm{E}} \tau \quad (17)$$

where E_{PT} (g m^{-2} d^{-1}) is the evapotranspiration rate calculated with the Priestly-Taylor method, α (dimensionless) is the Priestly-Taylor evapotranspiration proportionality constant, α_E (dimensionless) is the Priestly-Taylor evaporation proportionality constant. According to Tanner and Jury (1976), for wet, bare soil α_E equals α for full-cover vegetation, and it decreases under a canopy as percent cover and LAI increase and τ decreases, approaching unit at low value of τ. An α_E near unity would be expected when the canopy greatly decreases the wind and the saturation deficit near the soil surface. T_c (dimensionless) is τ at which the plant cover is large enough for $\alpha_E \approx 1$. A_E is calculated assuming linearity between α_E and τ:

$$\alpha_{\mathrm{E}} = \begin{cases} 1, & \tau \leq \tau_{\mathrm{c}} \\ \alpha - \left(\dfrac{(\alpha - 1)(1 - \tau)}{1 - \tau_{\mathrm{c}}} \right), & \tau > \tau_{\mathrm{c}} \end{cases} \quad (18)$$

6.2 Diffusion limited soil evaporation: Slosl

Once the surface has dried sufficiently to provide a significant barrier to water vapor diffusion, the evaporation from the diffusion limited soil (*Slosl*, g m^{-2} d^{-1}) is given by (Jamieson et al 1995b):

$$Slosl = \begin{cases} 8 \times 10^3, & \sum E_{\mathrm{soil}} \leq 0 \\ \left(\dfrac{2C^2}{\sum E_{\mathrm{soil}}} \right) \times 10^3, & \sum E_{\mathrm{soil}} < 25 \end{cases} \quad (19)$$

where $\sum E_{\mathrm{soil}}$ is the accumulated soil evaporation since the beginning of the diffusion limited soil evaporation phase, C (mm $d^{-1/2}$) is the soil diffusion constant, 10^3 convert kg to g.

7. Potential transpiration

Day-to-day variation of transpiration is associated mainly with variation in solar radiation, temperature and vapor pressure deficit. In the Ritchie model (Ritchie 1972) the potential transpiration rate (E_t) upper limit is given by the evapotranspiration rate (E_p). Restriction to E_t are associated with incomplete ground cover and stomatal restrictions. The latter is not taken into account (Jamieson et al 1995b) thus:

$$E_{\mathrm{t}} = E_{\mathrm{p}}(1 - \tau) \tag{20}$$

8. Restrictions to actual transpiration

*SiriusQuality*2 uses availability of water from the soil reservoir as a method to restrict transpiration as soil moisture is depleted. Water in the soil is distributed between layers through a percolation model (not described here) and in each layer it is described as plant available or unavailable water. The physical size of the available water reservoir is bounded by the advancing root front. Restrictions to actual transpiration are simulated through the calculation of a drought transpiration factor DTF calculated as:

$$\mathrm{DTF} = \begin{cases} 1, & \mathrm{FPAW} > P_{\mathrm{upper}}^{\mathrm{gs}} \\ 1 - \dfrac{\mathrm{FPAW} - P_{\mathrm{upper}}^{\mathrm{gs}}}{P_{\mathrm{lower}}^{\mathrm{gs}} - P_{\mathrm{upper}}^{\mathrm{gs}}}, & P_{\mathrm{upper}}^{\mathrm{gs}} \geq \mathrm{FPAW} \geq P_{\mathrm{lower}}^{\mathrm{gs}} \\ 0, & \mathrm{FPAW} < P_{\mathrm{lower}}^{\mathrm{gs}} \end{cases} \tag{21}$$

where FPAW (dimensionless) is the fraction of transpirable soil water, $P_{\mathrm{lower}}^{\mathrm{gs}}$ is the fraction of transpirable soil water for which the stomatal conduction equals zero, and $P_{\mathrm{upper}}^{\mathrm{gs}}$ is the fraction of transpirable soil water threshold for which the stomatal conductance starts to decrease. FPAW is calculated as:

$$\mathrm{FPAW} = 1 - \left(\frac{\mathrm{AWC} - \mathrm{AW}}{\mathrm{AWC}}\right) \tag{22}$$

where AWC (mm) is the maximum available water in root zone and AW (mm) is the actual available water in root zone. Calculations of AWC and AW are not described here.
In *SiriusQuality*2, DTF is not applied to E_{t} but instead to the quantity of soil water that can be extracted daily. Water may be extracted only within the root zone. In *SiriusQuality*2 root density is not considered to be a limiting factor in water uptake.

9. Evapotranspiration

According to the availability of wind and/or vapor pressure daily data, the *SiriusQuality*2 model calculates the evapotranspiration rate using the Penman (if wind and vapor pressure data are available) (Penman 1948) or the Priestly-Taylor (Priestley and Taylor 1972) method.

8.1 Priestly-Taylor evapotranspiration

The Priestly-Taylor (1972) evapotranspiration method is used when wind and/or vapor pressure daily data are not available. The evapotranspiration rate is calculated as:

$$E_{p,PT} = \alpha \frac{sR_N}{s+\gamma} \quad (23)$$

where s (hPa °C^{-1}) is the slope of saturated vapor pressure temperature curve at a given temperature T (°C), α is the Priestley-Taylor proportionality constant.

8.2 Penman evapotranspiration

The Penman (1948) method is used when wind and vapor pressure daily data are available. The evapotranspiration rate is calculated as:

$$E_{p,P} = \frac{E_{p,PT}}{\alpha} + 10^3 \frac{\rho \times C_p \times max(0, (e_s - e_d)) \times g_a}{\lambda(s+\gamma)} \quad (24)$$

where e_d (hPa) is the mean daily vapor pressure at the evaporating surface, e_s (hPa) is the mean daily saturated vapor pressure, and g_a (m d^{-1}) is the boundary layer conductance.

10. Slope of saturation vapour pressure curve

The slope of the relationship between e_s and the mean daily air temperature ($T_{a,mean}$, °C) (s, hPa) is calculated as (Murray, 1967):

$$s = \frac{4098 \times e_s}{\left(T_{a,mean} + 273.3\right)^2} \quad (25)$$

11. Saturation vapor pressure of water vapor

The saturation vapor pressure of the air at temperature T (°C) water is calculation according to the equation by Murray (1967):

$$e_s = 6.108 \times e^{\left(\frac{17.27 \times T}{T+237.3}\right)} \quad (26)$$

Because of the non-linearity of the above equation, the daily mean saturation vapor pressure is calculated as the mean between the saturation vapor pressure at the mean daily minimum ($T_{a,min}$, °C) and maximum ($T_{a,max}$, °C) air temperatures,

$$e_s = \frac{e_s(T_{a,min}) + e_s(T_{a,max})}{2} \quad (27)$$

12. Boundary layer conductance

The boundary layer conductance g_a is expressed as the wind speed profile above the canopy and the canopy structure. The approach does not take into account buoyancy effects. The equation described below includes already multiplication by ρ and C_p (4).

$$g_a = \frac{k^2 (u_a)}{\ln\left(\frac{z_m - d}{z_{om}}\right)\ln\left(\frac{z_h - d}{z_{oh}}\right)} \tag{28}$$

with,

$$z_{om} = 0.123h$$
$$z_{oh} = 0.1 z_{om}$$
$$d = 0.67h$$

where k (dimensionless) is the von Kármán constant, u_a (m d^{-1}) is wind speed, z_m (m) is the height of wind measurements, z_h (m) is the height of humidity measurements, d (m) is the zero-plane displacement, z_{om} (m) is the roughness length governing momentum transfer, z_{oh} is the roughness length governing transfer of heat and vapour, h (m) is the crop height.

13. Soil temperature

Daily maximum soil temperature of the current day d ($T_{s,max}(d)$, ºC) is calculated as:

$$T_{s,max}(d) = \begin{cases} T_{a,max} + 11.2 \times \left(1 - e^{-0.07\times(G\times10^{-3}\times\lambda - 5.5)}\right) - 0.5 \times T_{a,mean} + 4, & T_{a,mean} < 8 \\ T_{a,max} + 11.2 \times \left(1 - e^{-0.07\times(G\times10^{-3}\times\lambda - 5.5)}\right), & T_{a,mean} \geq 8 \end{cases} \tag{29}$$

Daily minimum soil temperature of the current day d ($T_{s,min}(d)$, ºC) is calculated as the average between $T_{a,min}$ of the current day d and the soil deep temperature ($T_{s,deep}(d-1)$, ºC) of the previous day d-1. The soil deep temperature of day *d-1* is calculated as:

$$T_{s,deep}(d-1) = \frac{\left(9T_{s,deep(d-2)} + \frac{T_{s,min(d-1)} + T_{s,max(d-1)}}{2}\right)}{10} \tag{30}$$

14. Mean daily air temperature

Mean daily air temperature is calculated as the sum of eight contributions each day of a cosinusoidal variation between maximum and minimum temperatures following Weir et al. (1984):

$$T_{\mathrm{a,mean}} = \frac{1}{8}\sum_{r=1}^{r=8}(T_h - T_b) \tag{31}$$

where

$$T_{\mathrm{h}}(r) = T_{min} + f_r(T_{max} - T_{min}) \tag{32}$$

And

$$f_{(r)} = \frac{1}{2}\left(1 + cos\frac{90}{8}(2r-1)\right) \tag{33}$$

T_b (°C) is the base temperature fixed at 0°C and T_h (°C) is the calculated three hour temperature contribution to estimated daily mean temperature, and $f_{(r)}$ is the fraction that each 3-h period during the day contributes to the thermal time for that day. Negative contributions of are treated as zero.

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ANNEXE

Table A1. List of variables used in SiriusQuality2 energy balance and canopy and soil temperature model

Symbol	Description	Units	Equation #
$\sum E_{soil}$	Accumulated soil evaporation since the beginning of diffusion limited soil evaporation phase	g	(19)
a	Factor of the slope of saturated vapor pressure	-	(26)
AW	Maximum available water in root zone	mm	(22)
AWC	Actual available water in root zone	mm	(22)
DTF	Reduction factor for soil water extraction by the plant	dimensionless	(21)
e_d	Vapor pressure at the evaporating surface	hPa	(24)
E_p	Evapotranspiration rate	g m^{-2} d^{-1}	(20)
$E_{p,P}$	Evapotranspiration rate calculated with the Penman method	g m^{-2} d^{-1}	(24)
$E_{p,PT}$	Evapotranspiration rate calculated with the Priestly-Taylor method	g m^{-2} d^{-1}	(17)(23)(24)
e_s	Mean saturated vapor pressure	hPa	(24)(25)(27)
E_{soil}	Soil evaporation	g m^{-2} d^{-1}	(14)(16)(19)
E_t	Transpiration rate	g m^{-2} d^{-1}	(2)(4)(6)(20)
f_r	Fraction that each 3-h period during the day contributes to the mean temperature for that day	dimensionless	(32) (33)
FPAW	Fraction of transpirable soil water	dimensionless	(21)(22)
G	Soil heat flux (in equivalent evaporation)	g m^{-2} d^{-1}	(1)(4)(6)(14)
g_a	Boundary layer conductance	m d^{-1}	(3)(4)(28)
h	Crop height	m	(28)
H	Sensible heat flux	g m^{-2} d^{-1}	(2)(3)(6)
LAI	Leaf area index	m^2 m^{-2}	(15)
N_{olr}	Net outgoing longwave radiation	MJ m^{-2} d^{-1}	(7)(9)
N_{sr}	Net shortwave radiation	MJ m^{-2} d^{-1}	(7)(8)
R_a	Extraterrestrial solar radiation	MJ m^{-2} d^{-1}	(12)
R_N	Net radiation (in equivalent evaporation)	g m^{-2} d^{-1}	(1)(4)(6)(7)(14)(23)
R_s	Incoming solar radiation	MJ m^{-2} d^{-1}	(8)(11)
R_{so}	Clear sky solar radiation	MJ m^{-2} d^{-1}	(11)
s	Slope of saturated vapor pressure temperature curve	hPa °C^{-1}	(23)(24)(25)

Table A1. Continued

$T_{0,K}$	Temperature in Kelvin at the triple point of water	K	(26)(27)
T_a	Air temperature	°C	(3)(4)(5)
$T_{a,K}$	Air temperature	K	(9)(26)(27)
$T_{a,max}$	Maximum air temperature	°C	(27)
$T_{a,mean}$	Mean air temperature	°C	(29) (31)
$T_{a,min}$	Minimum air temperature	°C	(27)
T_b	Base temperature	°C	(31)
T_c	Canopy temperature	°C	(3)(4)(5)
T_h	Calculated three hour temperature contribution to estimated daily mean temperature	°C	(31) (32)
$T_{max,K}$	Maximum air temperature	K	(10)
$T_{min,K}$	Minimum air temperature	K	(10)
$T_{s,deep}$	Deep soil temperature	°C	(30)
$T_{s,max}$	Maximum soil temperature	°C	(29)(30)
$T_{s,min}$	Minimum soil temperature	°C	(30)
u_a	Wind speed	m d^{-1}	(28)
VP	Vapor pressure	hPa	(13)
α_E	Priestly-Taylor evaporation proportionality factor	dimensionless	(17)(18)
τ	fraction of radiation intercepted by the crop	dimensionless	(14)(15)(17)(18)(20)
φ	Energy available to the crop	g m^{-2} d^{-1}	(1)(2)

Table A2. Symbols, units, description of the parameters.

Symbols used in the model description	Default value	Unit	Description
λ	2.454	MJ kg^{-1}	Latent heat of vaporization of water
ρ	1.225	kg m^{3}	Density of air
r	0.23	dimensionless	Albedo or canopy reflection coefficient
σ	4.903×10^{-9}	MJ K^{-4} m^{2} d^{-1}	Stefan-Boltzmann constant
K_L	0.43	m^{2}	Light extinction coefficient
α	1.50	dimensionless	Priestly-Taylor evapotranspiration proportionality constant
τ_c	0.3	dimensionless	τ at which the plant cover is large enough for $\alpha_E \approx 1$
C	4.20	mm d$^{-1/2}$	Soil diffusion constant
γ	0.66	hPa °C^{-1}	psychrometric constant (at 20°C and 1,013 hPa)
$T_{0,K}$	273.16	K	Triple point of water in Kelvin scale
c_p	0.00101	MJ kg^{-1} °C^{-1}	Specific heat capacity of dry air
k	0.41	dimensionless	von Kármán constant
$P_{\mathrm{lower}}^{\mathrm{gs}}$	0.1	Dimensionless	Fraction of transpirable soil water for which the stomatal conduction equals zero
$P_{\mathrm{upper}}^{\mathrm{gs}}$	0.5	Dimensionless	Fraction of transpirable soil water threshold for which the stomatal conductance starts to decrease
z_m	2.00	m	Height of wind measurements
z_h	2.00	m	Height of humidity measurements

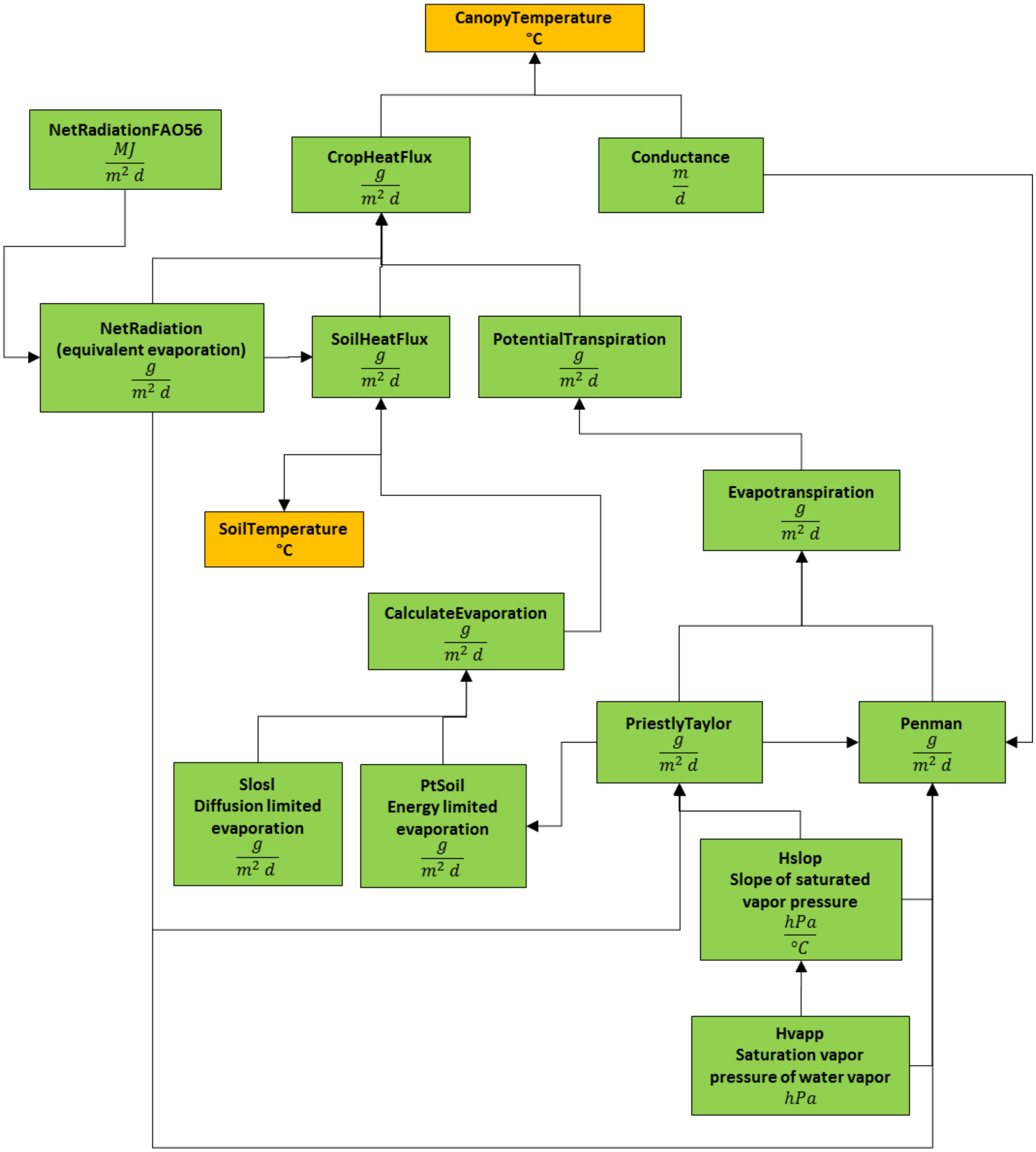

Figure A1. Relationships between the submodels of the energy balance and canopy temperature model. Box names are submodel names as they are implemented in the *SiriusQuality*2 software code. Units are output units. In orange the canopy temperature and the soil temperature submodel.