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A land surface model combined with a crop growth model for paddy rice (MATCRO-Rice v. 1) – Part 1: Model description

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Abstract. Crop growth and agricultural management can affect climate at various spatial and temporal scales through the exchange of heat, water, and gases between land and atmosphere. Therefore, simulation of fluxes for heat, water, and gases from agricultural land is important for climate simulations. A land surface model (LSM) combined with a crop growth model (CGM), called an LSM-CGM combined model, is a useful tool for simulating these fluxes from agricultural land. Therefore, we developed a new LSM-CGM combined model for paddy rice fields, the MATCRO-Rice model. The main objective of this paper is to present the full description of MATCRO-Rice. The most important feature of MATCRO-Rice is that it can consistently simulate latent and sensible heat fluxes, net carbon uptake by crop, and crop yield by exchanging variables between the LSM and CGM. This feature enables us to apply the model to a wide range of integrated issues.

1 Introduction

In the last 15 years, climate and land surface modelling studies have shown that crop growth and farm management in agricultural land significantly affect climate via the exchange of heat, water, and gases. For example, applying a regional climate model combined with a crop growth model (CGM) to the United States, Tsvetsinskaya et al. (2001) showed that crop growth can change the surface temperature by 2–4 °C. Maruyama and Kuwagata (2010) showed that crop growing season can affect the amount of evapotranspiration by using a land surface model (LSM) combined with a CGM. Levis et al. (2012) incorporated a CGM into an earth system model, and showed that the timing of crop sowing can change the amount of precipitation. Using a dynamic global vegetation model combined with a CGM, Bondeau et al. (2007) showed that the global carbon cycle, which has a significant effect on global warming, is largely modified by crop growth and farm management. Osborne et al. (2009), using a global climate model coupled with a CGM, demonstrated that the crop–climate interaction can affect annual variability in surface temperature. All these studies indicate that crop growth and farm management are key determinants of climate and that climate simulations need to simulate the fluxes of heat, water, and gases in agricultural land.

An LSM or dynamic vegetation model (DVM) incorporated with a CGM, called LSM-CGM or DVM-CGM combined models, are a useful tool for simulating the fluxes of heat, water, and gases in agricultural land. Hence, several LSMs and DVMs incorporated with a CGM have been developed (BATS-GF: Tsvetsinskaya et al., 2001; Agro-IBIS: Kucharik, 2003; ORCHIDEE-STICS: Gervois et al., 2004; LPJmL: Bondeau et al., 2007; GLAM-MOSES2: Osborne et al., 2007; SIBcrop: Lokupitiya et al., 2009; MK10: Maruyama and Kuwagata, 2010; CLM4CNcrop: Levis et al., 2012; JULES-crop: Osborne et al., 2015). Lei et al. (2010) divided these incorporated models into three types in terms of integration schemes for the leaf area index (LAI). Among these types, the type of models that consistently simulate crop production, LAI, water-energy flux, and carbon uptake by exchanging variables between an LSM and a CGM allows for wide applicability and comprehensive evaluation of the model with observations (Lei et al., 2010). However, this type comprises currently only four models: Agro-IBIS, SIBcrop, CLM4CNcrop, and JULES-crop. Among these, only JULES-crop can simulate the growth of rice, although rice is one of the major crops, accounting for 23 % of agricultural land farmed with cereals worldwide (FAO, 2015). Nevertheless, the JULES-crop model does not consider the flooded and irrigated surface of paddy rice fields, which is an important parameter when simulating heat and water fluxes in paddy rice fields, because heat and water fluxes in a flooded and irrigated surface are largely different from those in a non-flooded and rain-fed surface (e.g. Boucher et al., 2004; Lobell et al., 2006; Kueppers et al., 2008).

We developed a new LSM-CGM model, called MATCRO-Rice. The aim of this paper is to describe the MATCRO-Rice model in detail. The most important feature of MATCRO-Rice is that it can consistently simulate latent heat flux (LHF), sensible heat flux (SHF), net carbon uptake by crop, and crop yields by exchanging variables between the LSM and CGM. Herein, we first provide the overview of MATCRO-Rice in Sect. 2, and then describe the LSM and CGM of MATCRO-Rice in detail in Sects. 3 and 4, respectively. Last, we discuss the applications and limitations of MATCRO-Rice in Sect. 5. The model validation for MATCRO-Rice is described in the accompanied paper (Masutomi et al., 2016).

2 Model overview: MATCRO-Rice

MATCRO-Rice has two main components: LSM and CGM. The LSM component mainly simulates LHF and SHF. It is based on MATSIRO (Takata et al., 2003), which is embedded in global climate models (MIROC5.0: Watanabe et al., 2010; NICAM: Satoh et al., 2008) and a climate system model (MIROC-ESM: Watanabe et al., 2011). In addition, MATSIRO is used for a range of hydrological applications (e.g. Pokhrel et al., 2012; Hirabayashi et al., 2013).

The CGM of MATCRO-Rice mainly simulates rice yield and biomass for each organ during a growing period. The CGM used in MATCRO-Rice is based on CGMs developed by the school of de Wit (Bouman et al., 1996; e.g. MACROS: Penning de Vries et al., 1989; SUCROS: Goudriaan and van Laar, 1994; ORYZA2000: Bouman et al., 2001).

The meteorological inputs to run MATCRO-Rice are listed in Table 1. The standard outputs of MATCRO-Rice are LHF, SHF, biomass of organs during a growing period, and crop yield. All other variables simulated in MATCRO-Rice can be output if needed. The feature of MATCRO-Rice is to exchange variables between the LSM and CGM. The variables exchanged are listed in Table 2.

In the present paper, we describe MATCRO only for rice. The model structure of MATCRO, however, is valid for other crops. Therefore, MATCRO can be applied to other crops if the model parameters for other crops are given.

Table 1. Meteorological inputs.

Variable	Unit	Description
P_a	Pa	Air pressure
P_r	$\mathrm{kg\,m^{-2}\,s^{-1}}$	Precipitation
Q	$\mathrm{kg\,kg^{-1}}$	Specific humidity
$R_\mathrm{s}^\mathrm{d}(0)$	$\mathrm{W\,m^{-2}}$	Downward shortwave radiant flux density at the canopy top
$R_\mathrm{l}^\mathrm{d}(0)$	$\mathrm{W\,m^{-2}}$	Downward longwave radiant flux density at the canopy top
T_a	K	Air temperature
U	$\mathrm{m\,s^{-1}}$	Wind speed

3 Land surface model

The main outputs of the LSM of MATCRO-Rice are LHF and SHF. The LSM has five modules, which are energy balance at the canopy and surface, within-canopy shortwave radiation, bulk transfer coefficient for latent and sensible heat, canopy water balance, and soil water and heat transfer. Each module is described in detail in the following sections. Before describing each module, we note the following two major modifications from the original LSM, MATSIRO (Takata et al., 2003).

1. LAI, crop height, and root depth, which are constant in the original MATSIRO, are dynamically calculated in the CGM and are the inputs to the LSM.
2. Surface water is added above the soil surface in the case of flooded surface.

Other minor modifications are described separately in each of the following sections. Table 3 shows all the modifications of the original model. We note that the photosynthesis model used in MATCRO is described in the CGM section (Sect. 4).

3.1 Energy balance at the canopy and surface

This module calculates LHF and SHF by solving energy balance at two layers, canopy and surface. The module is based on the original MATSIRO (Takata et al., 2003), except for the addition of surface water above the soil in the case of flooded surface and other minor modifications. The energy balance at the canopy and surface are given as follows:

$$R_\mathrm{nc} = H_\mathrm{c} + \lambda E_\mathrm{c} + \lambda E_\mathrm{t},\ \text{(canopy)} \tag{1}$$

$$R_\mathrm{ng} = H_\mathrm{g} + \lambda E_\mathrm{g} + G_\mathrm{gs} + S_\mathrm{tw},\ \text{(surface)} \tag{2}$$

where R_nc and R_ng are the net radiant flux density at canopy and surface; H_c and H_g are the SHF from the canopy and surface; E_c, E_t, and E_g are the evaporation from wet canopy, transpiration from the canopy, and evaporation from the surface, respectively; G_gs is the heat flux from the surface to soil; and S_tw is the heat flux stored into surface water in the

Table 2. Variables exchanged between the land surface model (LSM) and crop growth model (CGM).

Variable	Unit	Description
LSM to CGM		
$D_1^{\mathrm{d}}(l)$	$\mathrm{W\,m^{-2}}$	direct downward radiant flux density for photosynthesis active radiation (PAR) at a leaf area index (LAI) depth of l
$S_1^{\mathrm{d}}(l)$	$\mathrm{W\,m^{-2}}$	scattered downward radiant flux density for PAR at a LAI depth of l
$S_1^{\mathrm{u}}(l)$	$\mathrm{W\,m^{-2}}$	scattered upward radiant flux density for PAR at a LAI depth of l
T_{c}	K	canopy temperature
CGM to LSM		
$\overline{g}_{\mathrm{s}}$	$\mathrm{m\,s^{-1}}$	stomatal conductance per unit leaf area for both sides of the leaf
h_{gt}	m	canopy height
L	$\mathrm{m^2\,m^{-2}}$	LAI
W_{sh}	$\mathrm{kg\,a^{-1}}$	dry matter weight of shoot
z_{rt}	m	root depth

Table 3. Modifications from the original model, MATSIRO.

Eq.	MATCRO	MATSIRO
11	Flooded surface	Not considered
15–19	Goudriaan and van Laar (1994)	Goudriaan (1977)
25	Watanabe (1994)	$\left[1/C_{H_{\mathrm{c}}}+U/(\overline{g}_{\mathrm{st}}L/2)\right]^{-1}$
31 and 32	Campbell and Norman (1998)	Unknown
36	Maruyama and Kuwagata (2008)	$\frac{\Theta_0 C_M^{3/2} U^2}{\kappa g C_{H_{\mathrm{g}}}(T_{\mathrm{g}}-T_{\mathrm{a}})}$
37	Campbell and Norman (1998)	300 K
45	Penning de Vries et al. (1989)	$0.2L$
50	Campbell and Norman (1998) and Best et al. (2011)	Default fixed values for each soil type are given
54	Flooded surface	Not considered
$55(z_{\mathrm{b}} < z \leq z_{\max})$	Hanasaki et al. (2008)	Beven and Kirkby (1979)
59	Calculated from the assumption that root has no spatial orientation	Default fixed values for each vegetation type are given
63–109	de Pury and Farquhar (1997) and Dai et al. (2004)	Sellers et al. (1992, 1996a)
110–141	Crop development and growth	Not considered

case of flooded surface. It is important to note that the downward flux for R_{nc}, R_{ng}, and G_{gs} indicates a positive flux, whereas downward flux for H_{c}, H_{g}, E_{c}, E_{t}, and E_{g} indicates a negative flux. All variables in the model are listed in Table 4. λ is the physical constant for the latent heat of vaporization (Table 5). Each of the radiant, heat, and water fluxes in Eqs. (1) and (2) are given by the following equations.

$$R_{\mathrm{nc}} = \left(R_{\mathrm{s}}^{\mathrm{d}}(0) - R_{\mathrm{s}}^{\mathrm{u}}(0)\right)(1-\tau_{\mathrm{cs}}) + \epsilon R_{\mathrm{l}}^{\mathrm{d}}(0)(1-\tau_{\mathrm{cl}}) - \left(2\epsilon\sigma T_{\mathrm{c}}^4 - \epsilon\sigma T_{\mathrm{g}}^4\right)(1-\tau_{\mathrm{cl}}), \tag{3}$$

$$R_{\mathrm{ng}} = \left(R_{\mathrm{s}}^{\mathrm{d}}(0) - R_{\mathrm{s}}^{\mathrm{u}}(0)\right)\tau_{\mathrm{cs}} + \epsilon R_{\mathrm{l}}^{\mathrm{d}}(0)\tau_{\mathrm{cl}} - \epsilon\sigma T_{\mathrm{g}}^4 + \epsilon\sigma(1-\tau_{\mathrm{cl}})T_{\mathrm{c}}^4, \tag{4}$$

$$H_{\mathrm{c}} = c_{\mathrm{pa}}\rho_{\mathrm{a}}C_{H_{\mathrm{c}}}U(T_{\mathrm{c}}-T_{\mathrm{a}}), \tag{5}$$

$$H_{\mathrm{g}} = c_{\mathrm{pa}}\rho_{\mathrm{a}}C_{H_{\mathrm{g}}}U\left(T_{\mathrm{g}}-T_{\mathrm{a}}\right), \tag{6}$$

$$E_{\mathrm{c}} = \min\{f_{\mathrm{cw}}\rho_{\mathrm{a}}C_{H_{\mathrm{c}}}U(Q_{\mathrm{sat}}(T_{\mathrm{c}},P_{\mathrm{a}})-Q), E_{\mathrm{c,max}}\}, \tag{7}$$

$$E_{\mathrm{t}} = \begin{cases} \min\{(1-f_{\mathrm{cw}})\rho_{\mathrm{a}}C_{E_{\mathrm{c}}}U(Q_{\mathrm{sat}}(T_{\mathrm{c}},P_{\mathrm{a}})-Q), E_{\mathrm{t,max}}\}, \\ \quad (\text{if } Q_{\mathrm{sat}}(T_{\mathrm{c}},P_{\mathrm{a}}) > Q) \\ (1-f_{\mathrm{cw}})\rho_{\mathrm{a}}C_{H_{\mathrm{c}}}U(Q_{\mathrm{sat}}(T_{\mathrm{c}},P_{\mathrm{a}})-Q), \\ \quad (\text{otherwise}) \end{cases} \tag{8}$$

$$E_{\mathrm{g}} = \begin{cases} \min\{\rho_{\mathrm{a}}C_{E_{\mathrm{g}}}U(h_{\mathrm{ms}}Q_{\mathrm{sat}}(T_{\mathrm{g}},P_{\mathrm{a}})-Q), E_{\mathrm{g,max}}\}, \\ \quad (\text{if } h_{\mathrm{s}}Q_{\mathrm{sat}}(T_{\mathrm{g}},P_{\mathrm{a}}) > Q) \\ \rho_{\mathrm{a}}C_{H_{\mathrm{g}}}U(h_{\mathrm{ms}}Q_{\mathrm{sat}}(T_{\mathrm{g}},P_{\mathrm{a}})-Q), \\ \quad (\text{otherwise}) \end{cases} \tag{9}$$

$$G_{\mathrm{gs}} = k_{\mathrm{w}}(T_{\mathrm{g}}-T_{\mathrm{s}}(0))/d_{\mathrm{w}}, \tag{10}$$

$$S_{\mathrm{tw}} = \begin{cases} c_{\mathrm{pw}}\rho_{\mathrm{w}}d_{\mathrm{w}}(\mathrm{d}T_{\mathrm{g}}/\mathrm{d}t), & (\text{flooded}), \\ 0 & (\text{unflooded}) \end{cases} \tag{11}$$

Table 4. Variables.

Symbol	Units	Eq.	Description
$\overline{A}_{\mathrm{g},x}$	$\mathrm{mol(CO_2)\,m^{-2}}(l)\,\mathrm{s^{-1}}$	68	gross primary production per unit leaf area of sunlit ($\overline{A}_{\mathrm{g,sn}}$) and shade($\overline{A}_{\mathrm{g,sh}}$) leaves
$\overline{A}_{\mathrm{g}',x}$	$\mathrm{mol(CO_2)\,m^{-2}}(l)\,\mathrm{s^{-1}}$	72	gross primary production without photosynthesis down-regulation per unit leaf area of sunlit ($\overline{A}_{\mathrm{g',sn}}$) and shade($\overline{A}_{\mathrm{g',sh}}$) leaves
A_n	$\mathrm{mol(CO_2)\,m^{-2}\,s^{-1}}$	63	net carbon assimilation
$\overline{A}_{\mathrm{n},x}$	$\mathrm{mol(CO_2)\,m^{-2}}(l)\,\mathrm{s^{-1}}$	64	net carbon assimilation per unit leaf area of sunlit ($\overline{A}_{\mathrm{n,sn}}$) and shade ($\overline{A}_{\mathrm{n,sh}}$) leaves
$A_{3,i}$	–	C8	variable for the calculation of coefficients of radiation equations (Eqs. C2 and C3)
A^+	–	E6	intermediate variable for the calculation of roughness
C_E	–	28	BTC for latent heat between the entire surface and atmosphere
C_{E_c}	–	25	BTC for latent heat between canopy and atmosphere
C_{E_g}	–	24	BTC for latent heat between surface and atmosphere
C_H	–	29	BTC for sensible heat between the entire surface and atmosphere
C_{H_c}	–	27	BTC for sensible heat between canopy and atmosphere
C_{H_g}	–	26	BTC for sensible heat between surface and atmosphere
C_M	–	38	BTC for momentum between the entire surface and atmosphere
$C_{M\mathrm{g}}$	–	39	BTC for momentum between surface and atmosphere
$C_{x,i}$	–	C2 to C5	coefficients of radiation equations (Eqs. 12–14; $x = 1, 2, 3, 4$)
C_X^0	–	E7	intermediate variable for the calculation of roughness (X denotes T or Q)
C_X^∞	–	E8	intermediate parameter for the calculation of roughness (X denotes T or Q)
c_a	Pa	98	partial pressure of atmospheric CO_2
c_e	–	E15	leaf transfer coefficient for specific humidity
$c_\mathrm{hs}(z)$	$\mathrm{J\,m^{-3}\,K^{-1}}$	50	volumetric heat capacity of soil at a depth of z
$c_{\mathrm{i},x}$	Pa	64 to 107	partial pressure of intercellular CO_2
$c_{\mathrm{s},x}$	Pa	97	partial pressure of CO_2 at leaf boundary
$D_i^\mathrm{d}(l)$	$\mathrm{W\,m^{-2}}$	12	radiant flux density for downward direct radiation for PAR ($i = 1$) or NIR ($i = 2$) at a leaf area index (LAI) depth of l
D_g	$\mathrm{kg\,m^{-2}\,s^{-1}}$	44	amount of water that falls from canopy onto surface due to gravity
D_oy	day	–	the number of days from 1 January
D_vr	K	112	development rate at t
D_vs	–	110	development stage at t
d	m	E1	zero-plane displacement height
E_c	$\mathrm{kg\,m^{-2}\,s^{-1}}$	7	evaporation from canopy
$E_\mathrm{c,max}$	$\mathrm{kg\,m^{-2}\,s^{-1}}$	7	maximum evaporation from canopy
E_g	$\mathrm{kg\,m^{-2}\,s^{-1}}$	9	evaporation from surface
$E_\mathrm{g,max}$	$\mathrm{kg\,m^{-2}\,s^{-1}}$	62	maximum evaporation from surface
E_t	$\mathrm{kg\,m^{-2}\,s^{-1}}$	8	transpiration from canopy
$E_\mathrm{t,max}$	$\mathrm{kg\,m^{-2}\,s^{-1}}$	61	maximum transpiration from canopy
e_a	Pa	105	atmospheric vapour pressure
e_i	Pa	106	vapour pressure in leaf
e_sat	Pa	107	saturated vapour pressure
$e_{\mathrm{s},x}$	Pa	103	vapour pressure at leaf boundary in sunlit ($e_\mathrm{s,sn}$) and shade ($e_\mathrm{s,sh}$) leaves
F_c	$\mathrm{kg\,m^{-2}\,s^{-1}}$	46	amount of water that falls from the canopy onto soil in the case of non-flooded surface
$F_\mathrm{s}(z)$	$\mathrm{m^3\,m^{-2}\,s^{-1}}$	55	water flux at a soil depth of z
F_X	–	E9	intermediate parameter for the calculation of roughness (X denotes T or Q)
f_cw	–	40	fraction of canopy that is wet
f_df	–	17	fraction of scattered radiation
f_dwn	–	69	factor of photosynthesis down regulation
f_int	–	43	interception efficiency of precipitation by canopy
$f_\mathrm{r}(z)$	–	59	root distribution at a soil depth of z
$f_\mathrm{s}(z)$	–	79	water stress function on photosynthesis at a soil depth of z
f_v	–	78	water stress factor on photosynthesis
G_ds	K s	111	growing degree seconds at t
$G_\mathrm{p,glu}$	$\mathrm{kg\,ha^{-1}\,s^{-1}}$	127 and 129	glucose partitioned to each organ
$G_\mathrm{r,glu}$	$\mathrm{kg\,ha^{-1}\,s^{-1}}$	127 and 129	growth rate of glucose reserves in leaves
$G_\mathrm{r,pnc}$	$\mathrm{kg\,ha^{-1}\,s^{-1}}$	124 and 128	growth rate of dry weight for panicles
$G_\mathrm{r,rot}$	$\mathrm{kg\,ha^{-1}\,s^{-1}}$	125 and 128	growth rate of dry weight for roots
$G_\mathrm{r,lef}$	$\mathrm{kg\,ha^{-1}\,s^{-1}}$	122 and 128	growth rate of dry weight for leaves
$G_\mathrm{r,stc}$	$\mathrm{kg\,ha^{-1}\,s^{-1}}$	126 and 128	growth rate of dry weight for starch reserves in stems
$G_\mathrm{r,stm}$	$\mathrm{kg\,ha^{-1}\,s^{-1}}$	123 and 128	growth rate of dry weight for stems
$G_\mathrm{s}(z)$	$\mathrm{W\,m^{-2}}$	49	heat flux at a soil depth of z
G_gs	$\mathrm{W\,m^{-2}}$	10	heat flux from surface to soil

Table 4. Continued.

Symbol	Units	Eq.	Description
$\overline{g}_{\mathrm{a}}$	$\mathrm{m\,s^{-1}}$	100	leaf boundary conductance per unit leaf area for both sides of the leaf
$\overline{g}_{\mathrm{l}}$	$\mathrm{mol\,m^{-2}}(l)\,\mathrm{s^{-1}}$	99	leaf boundary conductance for vapour per unit leaf area
$\overline{g}_{\mathrm{s}}$	$\mathrm{m\,s^{-1}}$	108	stomatal conductance per unit leaf area for both sides of the leaf
$\overline{g}_{\mathrm{st}}$	$\mathrm{mol\,m^{-2}}(l)\,\mathrm{s^{-1}}$	109	stomatal conductance for vapour per unit leaf area for both sides of the leaf
$\overline{g}_{\mathrm{st},x}$	$\mathrm{mol\,m^{-2}}(l)\,\mathrm{s^{-1}}$	101	stomatal conductance for vapour per unit leaf area in sunlit ($\overline{g}_{\mathrm{st,sn}}$) and shade ($\overline{g}_{\mathrm{st,sh}}$) leaves
H_{c}	$\mathrm{W\,m^{-2}}$	5	sensible heat flux from canopy
H_{g}	$\mathrm{W\,m^{-2}}$	6	sensible heat flux from surface
h_{gt}	m	139	canopy height
h_{arg}	rad	B3	hour angle from noon ($h_{\mathrm{r}} = 12$)
h_{ms}	–	60	humidity of topsoil
h_{r}	hour	–	local time at the simulation site
$h_{\mathrm{s},x}$	$\mathrm{Pa\,Pa^{-1}}$	102	relative humidity at leaf boundary in sunlit ($h_{\mathrm{s,sn}}$) and shade ($h_{\mathrm{s,sh}}$) leaves
I_{c}	$\mathrm{kg\,m^{-2}\,s^{-1}}$	42	amount of precipitation intercepted by canopy
$K(z)$	$\mathrm{kg\,s\,m^{-3}}$	56	hydraulic conductivity at a soil depth of z
K_{c}	Pa	85	Michaelis constant for $\mathrm{CO_2}$ fixation
$K_{\mathrm{e}}(z)$	–	52	Kersten number
K_{O}	Pa	86	Michaelis constant for $\mathrm{O_2}$ inhibition
$k_{\mathrm{ts}}(z)$	$\mathrm{W\,m^{-1}\,K^{-1}}$	51	thermal conductivity at a soil depth of z
L	$\mathrm{m^2\,m^{-2}}$	137	LAI
L_{MO}	m	35	Monin–Obukhov length of the entire surface
L_{MOg}	m	36	Monin–Obukhov length of surface
$L_{\mathrm{s,lef}}$	$\mathrm{kg\,ha^{-1}\,s^{-1}}$	133	loss rate of dry weight for leaves
L_{sn}	$\mathrm{m^2}(l)\,\mathrm{m^{-2}}$	65	LAI for sunlit leaves
L_{sh}	$\mathrm{m^2}(l)\,\mathrm{m^{-2}}$	66	LAI for shade leaves
l	$\mathrm{m^2}(l)\,\mathrm{m^{-2}}$	–	LAI depth from the top of canopy
$P_{\mathrm{r,sh}}$	–	130	ratio of glucose partitioned to shoot
$P_{\mathrm{r,pnc}}$	–	132	ratio of glucose partitioned to panicle from the glucose partitioned to shoot
$P_{\mathrm{r,lef}}$	–	131	ratio of glucose partitioned to leaf from the glucose partitioned to shoot
P_{1*}	–	E11	intermediate variable for the calculation of roughness ($*$ denotes M, T, or Q)
P_{2*}	–	E12	intermediate variable for the calculation of roughness ($*$ denotes M, T, or Q)
P_{3X}	–	E13	intermediate parameter for the calculation of roughness (X denotes T or Q)
P_{4X}	–	E13	intermediate parameter for the calculation of roughness (X denotes T or Q)
Q_{sat}	$\mathrm{kg\,kg^{-1}}$	A2	specific humidity at saturation
Q_{sn}	$\mathrm{mol\,m^{-2}\,s^{-1}}$	89	photon flux density for PAR absorbed by canopy in sunlit leaves
$Q_{\mathrm{sn,d}}$	$\mathrm{mol\,m^{-2}\,s^{-1}}$	91	direct PAR absorbed in sunlit leaves
$Q_{\mathrm{sn,s}}$	$\mathrm{mol\,m^{-2}\,s^{-1}}$	92	scattered PAR absorbed in shade leaves
Q_{sh}	$\mathrm{mol\,m^{-2}\,s^{-1}}$	90	photon flux density for PAR absorbed by canopy in shade leaves
$Q_{\mathrm{sh,s}}$	$\mathrm{mol\,m^{-2}\,s^{-1}}$	93	scattered PAR absorbed in shade leaves
$\overline{Q}_x$	$\mathrm{mol\,m^{-2}}(l)\,\mathrm{s^{-1}}$	88	photon flux density for PAR absorbed by leaves in sunlit ($\overline{Q}_{\mathrm{sn}}$) and shade ($\overline{Q}_{\mathrm{sh}}$) leaves
q_{t}	–	80	function that represents temperature dependence
$\overline{R}_{\mathrm{d},x}$	$\mathrm{mol(CO_2)\,m^{-2}}(l)\,\mathrm{s^{-1}}$	94	respiration in sunlit ($\overline{R}_{\mathrm{d,sn}}$) and shade ($\overline{R}_{\mathrm{d,sh}}$) leaves
R_{ex}	$\mathrm{W\,m^{-2}}$	19	extraterrestrial radiation
$R_{\mathrm{m,stc}}$	$\mathrm{kg\,ha^{-1}\,s^{-1}}$	134	remobilization rate of dry weight from starch reserves
R_{nc}	$\mathrm{W\,m^{-2}}$	3	net radiant flux density at canopy
R_{ng}	$\mathrm{W\,m^{-2}}$	4	net radiant flux density at surface
$R_{\mathrm{l}}^{\mathrm{d}}(l)$	$\mathrm{W\,m^{-2}}$	21	radiant flux density for downward longwave at a LAI depth of l
$R_{\mathrm{s}}^{\mathrm{d}}(l)$	$\mathrm{W\,m^{-2}}$	21	radiant flux density for downward shortwave at a LAI depth of l
$R_{\mathrm{s}}^{\mathrm{u}}(l)$	$\mathrm{W\,m^{-2}}$	21	radiant flux density for upward shortwave at a LAI depth of l
$r_{\mathrm{dd,lef}}$	$\mathrm{s^{-1}}$	135	ratio of dead leaf
r_{ij}	–	D1 and D2	reflectivity of canopies ($i = 1$: PAR; $i = 2$: NIR; $j = 1$: direct; $j = 2$: scattered)
r_{s}	–	30	resistance of topsoil to evaporation
S	–	87	Ratio of RuBP partitioned to carboxylase or oxygenase
$S_i^{\mathrm{d}}(l)$	$\mathrm{W\,m^{-2}}$	13	radiant flux density for downward scattered radiation for PAR($i = 1$) or NIR ($i = 2$) at a LAI depth of l
$S_i^{\mathrm{u}}(l)$	$\mathrm{W\,m^{-2}}$	14	radiant flux density for upward scattered radiation for PAR($i = 1$) or NIR ($i = 2$) at a LAI depth of l
S_{glu}	$\mathrm{kg\,ha^{-1}\,s^{-1}}$	119	supply of glucose to the reserves in leaf
S_{lw}	$\mathrm{kg\,m^{-2}}(l)$	138	specific leaf area
$S_{\mathrm{s}}(z)$	$\mathrm{m^3\,m^{-3}\,s^{-1}}$	58	absorption for transpiration by root at a soil depth of z
S_{tw}	$\mathrm{W\,m^{-2}}$	11	heat flux stored in surface water

Table 4. Continued.

Symbol	Units	Eq.	Description
T_c	K	3 to 11	canopy temperature
$T_\mathrm{s}(z)$	K	48	soil temperature at a soil depth of z
T_x	K	A2	temperature of canopy (T_c) or surface (T_g)
T_g	K	3 to 11	surface temperature
t	s	–	time
t_e	s	–	time at emergence after sowing
U_c	$\mathrm{m\,s^{-1}}$	F1	wind speed in the canopy
U_h	$\mathrm{m\,s^{-1}}$	F2	reference wind speed
$V_\mathrm{max}(l)$	$\mathrm{mol(CO_2)\,m^{-2}}(l)\,\mathrm{s^{-1}}$	83	reference value for maximum RuBisCO capacity at a LAI depth of l
$\overline{V}_{\mathrm{max},x}$	$\mathrm{mol(CO_2)\,m^{-2}}(l)\,\mathrm{s^{-1}}$	81 and 82	reference value for maximum RuBisCO capacity per unit leaf area of sunlit and shade leaves
$\overline{V}_{\mathrm{mc},x}$	$\mathrm{mol(CO_2)\,m^{-2}}(l)\,\mathrm{s^{-1}}$	76	maximum RuBisCO capacity per unit leaf area of sunlit ($\overline{V}_\mathrm{mc,sn}$) and shade ($\overline{V}_\mathrm{mc,sh}$) leaves for $\overline{\varpi}_{\mathrm{c},x}$
$\overline{V}_{\mathrm{ms},x}$	$\mathrm{mol(CO_2)\,m^{-2}}(l)\,\mathrm{s^{-1}}$	77	maximum RuBisCO capacity per unit leaf area of sunlit ($\overline{V}_\mathrm{ms,sn}$) and shade ($\overline{V}_\mathrm{ms,sh}$) leaves for $\overline{\varpi}_{\mathrm{s},x}$
W_glu	$\mathrm{kg\,ha^{-1}}$	118	dry weight of glucose reserves in leaves
W_pnc	$\mathrm{kg\,ha^{-1}}$	115	dry weight of panicles
$W_\mathrm{pnc,mt}$	$\mathrm{kg\,ha^{-1}}$	–	dry weight of panicles at maturity
W_rot	$\mathrm{kg\,ha^{-1}}$	116	dry weight of roots
W_sh	$\mathrm{kg\,ha^{-1}}$	136	dry weight of shoot
W_stc	$\mathrm{kg\,ha^{-1}}$	117	dry weight of starch reserves in stems
W_stm	$\mathrm{kg\,ha^{-1}}$	114	dry weight of stems
w_c	m	41	amount of water stored in canopy
w_cap	m	45	canopy water capacity
$w_\mathrm{s}(z)$	$\mathrm{m^3\,m^{-3}}$	53	volumetric concentration of soil water at a soil depth of z
Y_ld	$\mathrm{kg\,ha^{-1}}$	141	crop yield
z	m	–	soil depth
z_M	m	E2	roughness length of the entire surface for momentum profile
$z_{M\mathrm{g}}$	m	E4	roughness length that express the effect of water surface on the profile of momentum
z_M^+	m	E10	intermediate variable for the calculation of roughness
z_Q	m	E3	roughness length of the entire surface for specific humidity profile
z_rt	m	140	root depth
z_T	m	E3	roughness length of the entire surface for temperature profile
$z_{T\mathrm{g}}$	m	E5	roughness length that express the effect of water surface on the profile of temperature
z_X^+	m	E10	intermediate variable for the calculation of roughness (X denotes T or Q)
z_*^+	m	E10	intermediate variable for the calculation of roughness ($*$ denotes M, T, or Q)
δ_s	rad	B2	declination of the sun
Γ^*	Pa	84	light compensation point
γ_m	–	F3	coefficient of exponential decrease for wind speed in the canopy
$\overline{\varpi}_{\mathrm{c},x}$	$\mathrm{mol(CO_2)\,m^{-2}}(l)\,\mathrm{s^{-1}}$	73	RuBisCO-limited assimilation in sunlit ($\overline{\varpi}_\mathrm{c,sn}$) and shade ($\overline{\varpi}_\mathrm{c,sh}$) leaves
$\overline{\varpi}_{\mathrm{e},x}$	$\mathrm{mol(CO_2)\,m^{-2}}(l)\,\mathrm{s^{-1}}$	74	light-limited assimilation in sunlit ($\overline{\varpi}_\mathrm{e,sn}$) and shade ($\overline{\varpi}_\mathrm{e,sh}$) leaves
$\overline{\varpi}_{\mathrm{p},x}$	$\mathrm{mol(CO_2)\,m^{-2}}(l)\,\mathrm{s^{-1}}$	71	RuBisCO- and light-limited assimilation in sunlit ($\overline{\varpi}_\mathrm{p,sn}$) and shade ($\overline{\varpi}_\mathrm{p,sh}$) leaves
$\overline{\varpi}_{\mathrm{s},x}$	$\mathrm{mol(CO_2)\,m^{-2}}(l)\,\mathrm{s^{-1}}$	75	sucrose limited assimilation for sunlit ($\overline{\varpi}_\mathrm{s,sn}$) and shade ($\overline{\varpi}_\mathrm{s,sh}$) leaves
Ψ_E	–	32	diabatic correction factor for vapour
Ψ_H	–	32	diabatic correction factor for heat
Ψ_M	–	31	diabatic correction factor for momentum
$\psi(z)$	$\mathrm{J\,kg^{-1}}$	57	water potential at a soil depth of z
ρ_a	$\mathrm{kg\,m^{-3}}$	A1	air density
τ_atm	–	18	transmissivity of atmosphere
τ_cs	–	20	transmissivity of canopy for shortwave radiation
τ_cl	–	23	transmissivity of canopy for longwave radiation
τ_{ij}	–	D3 and D4	transmissivity of canopy ($i=1$: PAR; $i=2$: NIR; $j=1$: direct; $j=2$: scattered)
Θ_0	K	37	potential temperature
θ	rad	B1	zenith angle of the sun
ζ	–	33	atmospheric stability between the entire canopy and atmosphere
ζ_g	–	34	atmospheric stability between surface and atmosphere

Table 5. Physical and chemical constants.

Variable	Value	Units	Description
$C_{CO_2,glu}$	1.08×10^6	$kg\,ha^{-1}\,h^{-1}$ / $(mol\,m^{-2}\,s^{-1})$	conversion factor from CO_2 to glucose
$C_{glu,stc}$	0.9	$kg\,ha^{-1}$ / $(kg\,ha^{-1})$	conversion factor of dry weight from glucose to starch
$C_{stc,glu}$	1.11	$kg\,ha^{-1}$ / $(kg\,ha^{-1})$	conversion factor of dry weight from starch to glucose
c_{pa}	1004.6	$J\,K^{-1}\,kg^{-1}$	specific heat of air
c_{pw}	4200	$J\,K^{-1}\,kg^{-1}$	specific heat of water
g	9.8	$m\,s^{-1}$	gravitational constant
$e_{sat}(T_0)$	611	Pa	vapour pressure at melting temperature of water
k_q	4.6×10^{-6}	$(mol\,m^{-2}\,s^{-1})$ / $(W\,m^{-2})$	transfer constant from radiant flux density to photon flux density
k_w	0.6	$W\,m^{-1}\,K^{-1}$	thermal conductivity of water
R_{dry}	287.04	$J\,kg^{-1}\,K^{-1}$	gas constant of dry air
R_{sun}	1370	$W\,m^{-2}$	solar constant
R_{vap}	461	$J\,kg^{-1}\,K^{-1}$	gas constant of vapour
T_0	273.15	K	melting temperature of water
w_{H_2O}	0.018	$kg\,mol^{-1}$	molar weight of vapour
κ	0.4	–	Karman constant
λ	2.5×10^6	$J\,kg^{-1}$	latent heat of vaporization
ρ_w	1000	$kg\,m^{-3}$	water density
σ	5.67×10^{-8}	$W\,m^{-2}\,K^{-4}$	Boltzmann constant

where $R_s^d(0)$, $R_l^d(0)$, and $R_s^u(0)$ are the downward shortwave radiant flux density, downward longwave radiant flux density, and upward shortwave radiant flux density at the canopy top, respectively; τ_{cs} and τ_{cl} are the canopy transmissivity for shortwave and longwave radiation, respectively; C_{H_c} and C_{H_g} are the bulk transfer coefficients (BTCs) for sensible heat between canopy and atmosphere and between surface and atmosphere, respectively; C_{E_c} and C_{E_g} are the BTCs for latent heat between canopy and atmosphere and between surface and atmosphere, respectively; T_a, P_a, U, and Q are air temperature, air pressure, wind speed, and specific humidity, respectively; f_{cw} is the fraction of wet canopy; h_{ms} is humidity of the topsoil; T_c, T_g, and $T_s(0)$ are the canopy, surface, and topsoil temperature, respectively; $E_{t,max}$, $E_{g,max}$, and $E_{c,max}$ are the maximum transpiration from canopy, the maximum evaporation from surface, and the maximum evaporation from the canopy, respectively; c_{pa} and c_{pw} are the specific air and water heat, respectively; k_w is the water thermal conductivity; ρ_w and ρ_a are water and air density, respectively; σ is the Boltzmann constant; Q_{sat} is specific humidity at saturation; d_w is the depth of surface water in the case of flooded surface; ϵ is the longwave emissivity of surface; and d/dt indicates the time differentiation. The argument of the radiant flux density denotes LAI depth from the canopy top, and the argument of soil temperature denotes soil depth from the soil surface. Therefore, $R_s^d(0)$, $R_l^d(0)$, and $R_s^u(0)$ indicate the radiant flux density at the canopy top, and $T_s(0)$ indicates the soil surface temperature.

T_a, P_a, U, Q, $R_s^d(0)$, and $R_l^d(0)$ are meteorological forcing inputs (Table 1). $R_s^u(0)$, τ_{cs}, τ_{cl}, f_{cw}, h_{ms}, C_{E_c}, C_{E_g}, C_{H_c}, C_{H_g}, $T_s(0)$, $E_{t,max}$, $E_{g,max}$, and $E_{c,max}$ are calculated from Eqs. (21), (20), (23), (40), (60), (25), (24), (27), (26), (48), (61), (62), and (47), respectively, which are given in the following sections. The variables ρ_a and Q_{sat} are physically calculated from the air temperature and air pressure (Appendix A); c_{pa}, c_{pw}, k_w, ρ_w, and σ are physical constants (Table 5); d_w is a simulation setting parameter (Table 6); and ϵ is set to 0.96 (Campbell and Norman, 1998). T_c and T_g are numerically determined to satisfy Eqs. (1)–(11). The numerical method is described in Masutomi et al. (2016).

Irrigation and flooded surface start at $D_{oy,Is}$ and end at $D_{oy,Ie}$. $D_{oy,Is}$ and $D_{oy,Ie}$ are simulation setting parameters.

3.2 Within-canopy shortwave radiation

The main role of this module is to simulate direct downward photosynthesis active radiation (PAR), scattered downward PAR, and scattered upward PAR at a LAI depth of l from the canopy top by calculating the transmission and reflection of shortwave radiation by leaves within canopies. These PARs are used for calculating carbon assimilation in the CGM (Sect. 4.1). In addition to the simulation of PARs, transmissivities for shortwave and longwave radiation are simulated in this module. The transmissivities are used for calculating LHF and SHF (Sect 3.1).

This module is based on the simple model developed by Watanabe and Ohtani (1995). The model determines radiation within canopies by calculating the transmission and reflection of the radiation within the canopy. In this model, radiation within the canopy is divided into three components (downward direct, downward scattered, and upward scattered) and two wavebands (PAR and near infrared (NIR)).

Table 6. Parameters.

Variable	Value	Units	Description	Source
Simulation setting				
$C_{\mathrm{a,ppm}}$	–	ppm	atmospheric CO$_2$ concentration	Masutomi et al. (2016)
$D_{\mathrm{oy,Ie}}$	–	DOY	DOY of the day that irrigation and flooded surface end	Masutomi et al. (2016)
$D_{\mathrm{oy,Is}}$	–	DOY	DOY of the day that irrigation and flooded surface start	Masutomi et al. (2016)
$D_{\mathrm{oy,sw}}$	–	DOY	DOY of sowing day	Masutomi et al. (2016)
d_{w}	–	m	depth of surface water	Masutomi et al. (2016)
L_{t}	–	°	latitude of the simulation site	Masutomi et al. (2016)
$W_{\mathrm{glu,0}}$	–	kg ha^{-1}	dry weight of glucose reserve at emergence	Masutomi et al. (2016)
$W_{\mathrm{lef,0}}$	–	kg ha^{-1}	dry weight of leaf at emergence	Masutomi et al. (2016)
$W_{\mathrm{rot,0}}$	–	kg ha^{-1}	dry weight of root at emergence	Masutomi et al. (2016)
$W_{\mathrm{stm,0}}$	–	kg ha^{-1}	dry weight of stem at emergence	Masutomi et al. (2016)
z_{a}	–	m	reference height at which wind speed is observed	Masutomi et al. (2016)
z_{max}	–	m	depth of soil layer	Masutomi et al. (2016)
z_{t}	–	m	depth of the soil surface layer	Masutomi et al. (2016)
z_{b}	–	m	depth from the soil surface to the upper bound of the bottom-most layer of soil	Masutomi et al. (2016)
δt	–	s	time resolution	Masutomi et al. (2016)
Soil-type specific				
B	–	–	factor for hydraulic conductivity and water potential	Masutomi et al. (2016)
K_{s}	–	kg s m^{-3}	hydraulic conductivity at saturation	Masutomi et al. (2016)
w_{sat}	–	m^3 m^{-3}	volumetric concentration of soil water at saturation	Masutomi et al. (2016)
w_{wlt}	–	m^3 m^{-3}	volumetric concentration of soil water at the wilting point	Masutomi et al. (2016)
ψ_{s}	–	J kg^{-1}	water potential at saturation	Masutomi et al. (2016)
ρ_{s}	–	kg m^{-3}	soil bulk density	Masutomi et al. (2016)
Crop specific (paddy rice)				
b	0.01	mol m^{-2} s^{-1}	intercept of the Ball–Berry model	Sellers et al. (1996b)
$C_{\mathrm{glu,lef}}$	0.955	kg ha^{-1} / (kg ha^{-1})	conversion factor of dry weight from glucose to leaf	Penning de Vries et al. (1989)
$C_{\mathrm{glu,pnc}}$	0.821	kg ha^{-1} / (kg ha^{-1})	conversion factor of dry weight from glucose to panicle	Penning de Vries et al. (1989)
$C_{\mathrm{glu,rot}}$	0.928	kg ha^{-1} / (kg ha^{-1})	conversion factor of dry weight from glucose to root	Penning de Vries et al. (1989)
$C_{\mathrm{glu,stm}}$	0.928	kg ha^{-1} / (kg ha^{-1})	conversion factor of dry weight from glucose to stem	Penning de Vries et al. (1989)
c_{h}	0.06	–	leaf transfer coefficient for heat	Kimura and Kondo (1998)
c_{m}	0.2	–	leaf transfer coefficient for momentum	Kimura and Kondo (1998)
$D_{\mathrm{vs,rot1}}$	Parameterized	–	1st point of D_{vs} at which the partition to root changes	Masutomi et al. (2016)
$D_{\mathrm{vs,rot2}}$	Parameterized	–	2nd point of D_{vs} at which the partition to root changes	Masutomi et al. (2016)
$D_{\mathrm{vs,lef1}}$	Parameterized	–	1st point of D_{vs} at which the partition to leaf changes	Masutomi et al. (2016)
$D_{\mathrm{vs,lef2}}$	Parameterized	–	2nd point of D_{vs} at which the partition to leaf changes	Masutomi et al. (2016)
$D_{\mathrm{vs,pnc1}}$	Parameterized	–	1st point of D_{vs} at which the partition to panicle changes	Masutomi et al. (2016)
$D_{\mathrm{vs,pnc2}}$	Parameterized	–	2nd point of D_{vs} at which the partition to panicle changes	Masutomi et al. (2016)
$D_{\mathrm{vs,e}}$	Parameterized	–	D_{vs} at emergence	Masutomi et al. (2016)
f_{d}	0.015	–	respiration factor	Sellers et al. (1996b)
f_{stc}	Parameterized	–	fraction of glucose allocated to starch reserves	Masutomi et al. (2016)
h_{aa}	Parameterized	–	parameter for relation between leaf area index (LAI) and height before heading	Masutomi et al. (2016)
h_{ab}	Parameterized	–	parameter for relation between LAI and height before heading	Masutomi et al. (2016)
h_{ba}	Parameterized	–	parameter for relation between LAI and height after heading	Masutomi et al. (2016)
h_{bb}	Parameterized	–	parameter for relation between LAI and height after heading	Masutomi et al. (2016)
$D_{\mathrm{vs,h}}$	Parameterized	–	D_{vs} at heading	Masutomi et al. (2016)
k_{yld}	Parameterized	–	ratio of crop yield to dry weight of panicle at maturity	Masutomi et al. (2016)
$k_{S_{\mathrm{lw}}}$	Parameterized	–	parameter for the relation between S_{lw} and D_{vs}	Masutomi et al. (2016)
m	9	–	the slope of the Ball–Berry model	Sellers et al. (1996b)
$G_{\mathrm{ds,m}}$	Parameterized	K s	growing degree second at maturity	Masutomi et al. (2016)
P_{rot}	Parameterized	–	ratio of glucose partitioned to root	Masutomi et al. (2016)
P_{lef}	Parameterized	–	ratio of glucose partitioned to leaf from glucose partitioned to shoot	Masutomi et al. (2016)
$r_{\mathrm{d1,lef}}$	Parameterized	s^{-1}	ratio of dead leaf at harvest	Masutomi et al. (2016)
$r_{\mathrm{rm,stc}}$	1.16×10^{-6}	s^{-1}	ratio of remobilization	Bouman et al. (2001)
r_{rt}	1.16×10^{-7}	m s^{-1}	growth ratio of root	Penning de Vries et al. (1989)

Table 6. Continued.

Variable	Value	Units	Description	Source
r_1	0.105	–	leaf reflectivity for photosynthesis active radiation (PAR)	Sellers et al. (1996b)
r_2	0.58	–	leaf reflectivity for near infrared radiation (NIR)	Sellers et al. (1996b)
$S_{\mathrm{lw,mx}}$	Parameterized	$\mathrm{kg\,m^{-2}}$	maximum specific leaf area	Masutomi et al. (2016)
$S_{\mathrm{lw,mn}}$	Parameterized	$\mathrm{kg\,m^{-2}}$	minimum specific leaf area	Masutomi et al. (2016)
s_1	Parameterized	$\mathrm{K^{-1}}$	temperature dependence of $\overline{V}_{\mathrm{max},x}$ on $\overline{V}_{\mathrm{mc},x}$	Masutomi et al. (2016)
s_2	Parameterized	K	temperature dependence of $\overline{V}_{\mathrm{max},x}$ on $\overline{V}_{\mathrm{mc},x}$	Masutomi et al. (2016)
s_4	281	K	temperature dependence of $\overline{V}_{\mathrm{max},x}$ on $\overline{V}_{\mathrm{ms},x}$	Sellers et al. (1996b)
T_{b}	281.15	K	minimum temperature for development	Bouman et al. (2001)
T_{h}	313.15	K	maximum temperature for development	Bouman et al. (2001)
T_{o}	303.15	K	optimal temperature for development	Bouman et al. (2001)
$D_{\mathrm{vs,tr}}$	Parameterized	–	D_{vs} at transplanting and at which transplanting shock starts	Masutomi et al. (2016)
$D_{\mathrm{vs,te}}$	Parameterized	–	D_{vs} at which transplanting shock ends	Masutomi et al. (2016)
t_1	0.07	–	leaf transmissivity for PAR	Sellers et al. (1996b)
t_2	0.25	–	leaf transmissivity for NIR	Sellers et al. (1996b)
$V_{\mathrm{max}}(0)$	Parameterized	$\mathrm{\mu mol\,m^{-2}\,s^{-1}}$	maximum RuBisCO capacity at the canopy top	Masutomi et al. (2016)
$z_{\mathrm{rt,mx}}$	0.3	m	maximum root depth	Penning de Vries et al. (1989)
β_{ce}	0.98	–	GPP transition factor	Sellers et al. (1996b)
ϵ_{e}	0.08	$\mathrm{mol\,mol^{-1}}$	quantum efficiency	Sellers et al. (1996b)
Others				
$A_{x,i}$	C6–C7	–	coefficients of radiation equations (Eqs. 12–14; $x = 1, 2$)	Watanabe and Ohtani (1995)
a_i	C1	–	extinction coefficient for scattered radiation	Watanabe and Ohtani (1995)
C_0	288	ppm	base concentration of $\mathrm{CO_2}$ for photosynthesis down-regulation	Arora et al. (2009)
c_{pm}	870	$\mathrm{J\,kg^{-1}\,K^{-1}}$	specific heat of soil minerals	Campbell and Norman (1998)
D_1	1.14×10^{-11}	–	coefficient related to gravitational fall of canopy water	Rutter et al. (1975)
D_2	3.7×10^{3}	–	coefficient related to gravitational fall of canopy water	Rutter et al. (1975)
d_{f}	$\sec(2\pi(53/360))$	–	scattered factor	Watanabe and Ohtani (1995)
F	0.5	–	distribution of leaf orientation	Goudriaan and van Laar (1994)
K_{n}	0.3	–	vertical distribution of nitrogen	Oleson and Lawrence (2013)
k_{ts0}	0.25	$\mathrm{W\,m^{-1}\,K^{-1}}$	thermal conductivity of dry soil	Campbell and Norman (1998)
k_{tss}	1.58	$\mathrm{W\,m^{-1}\,K^{-1}}$	thermal conductivity of saturated soil	Best et al. (2011)
$[\mathrm{O_2}]$	20 900	Pa	partial pressure of intercellular $\mathrm{O_2}$	Collatz et al. (1991)
r_{g}	0.1	–	albedo of surface for shortwave radiation	Maruyama and Kuwagata (2010)
s_3	0.2	$\mathrm{K^{-1}}$	temperature dependence of $\overline{V}_{\mathrm{max},x}$ on $\overline{V}_{\mathrm{ms},x}$	Masutomi et al. (2016)
s_5	1.3	$\mathrm{K^{-1}}$	temperature dependence on $\overline{R}_{\mathrm{d},x}$	Sellers et al. (1996b)
s_6	328	K	temperature dependence on $\overline{R}_{\mathrm{d},x}$	Sellers et al. (1996b)
$z_{M\mathrm{s}}$	0.001	m	roughness length of surface for momentum	Kimura and Kondo (1998)
$z_{Q\mathrm{s}}$	0.001	m	roughness length of surface for specific humidity	Kimura and Kondo (1998)
$z_{T\mathrm{s}}$	0.001	m	roughness length of surface for heat	Kimura and Kondo (1998)
β_{pc}	0.95	–	GPP transition factor	Sellers et al. (1996b)
ϵ	0.96	–	longwave emissivity of surface	Campbell and Norman (1998)
γ_{d}	0.9	–	response parameter to elevated $\mathrm{CO_2}$	Arora et al. (2009)
γ_{gd}	0.42	–	response parameter to elevated $\mathrm{CO_2}$	Arora et al. (2009)
τ_{b}	8.64×10^{6}	s	recession constant for base water flow (100 days)	Hanasaki et al. (2008)

In addition, the following three assumptions are considered in the model for simplicity.

1. Leaf orientation is random (i.e. spherical distribution).
2. Leaf reflectivity and transmissivity of the radiation are vertically uniform within a canopy.
3. Scattered radiation is incoming from a zenith angle of 53°.

The first assumption may affect the accuracy of the model simulations. We know that leaf orientation of crops varies with their growth. However, there are no data on the change in leaf orientation for rice. Therefore, we assumed that the leaf orientation is random during the growing period. Assumption 3 is based on the fact that radiant flux uniformly emitted from a horizontal plane is approximately equal to radiant flux density from a zenith angle of 53°. From the three assumptions above, we can express analytically the radiant flux density for downward direct ($D_i^{\mathrm{d}}(l)$), downward scattered ($S_i^{\mathrm{d}}(l)$), and upward scattered ($S_i^{\mathrm{u}}(l)$) within canopy for each waveband ($i = 1$: PAR; $i = 2$: NIR) as follows:

$$D_i^{\mathrm{d}}(l) = D_i^{\mathrm{d}}(0)\exp(-Fl\sec(\theta)), \tag{12}$$

$$S_i^{\mathrm{d}}(l) = C_{1,i}\exp(a_i l) + C_{2,i}\exp(-a_i l) + C_{3,i} D_i^{\mathrm{d}}(l), \tag{13}$$

$$\begin{aligned} S_i^{\mathrm{u}}(l) =& A_{1,i}C_{1,i}\exp(a_i l) + A_{2,i}C_{2,i}\exp(-a_i l) \\ & + C_{4,i}D_i^{\mathrm{d}}(l). \end{aligned} \tag{14}$$

Here, F is a parameter for the distribution of leaf orientation. If we assume spherical distribution for leaf orientation as mentioned above, we have $F = 0.5$ (Goudriaan and van Laar, 1994). The variable l is a LAI depth from the canopy top. The variable θ is a zenith angle of the sun (Appendix B). The function sec indicates the secant function. The coefficients a_i, $C_{1,i}$, $C_{2,i}$, $C_{3,i}$, $C_{4,i}$, $A_{1,i}$, and $A_{2,i}$ are calculated as shown in Appendix C. It should be noted that a_i indicates the extinction coefficient for scattered radiation. $D_i^{\mathrm{d}}(0)$ is obtained by splitting radiant flux density for downward shortwave at the top of the canopy into direct and scattered radiation as follows:

$$D_i^{\mathrm{d}}(0) = 0.5R_{\mathrm{s}}^{\mathrm{d}}(0)(1 - f_{\mathrm{df}}), \tag{15}$$

$$S_i^{\mathrm{d}}(0) = 0.5R_{\mathrm{s}}^{\mathrm{d}}(0)f_{\mathrm{df}}, \tag{16}$$

where $R_{\mathrm{s}}^{\mathrm{d}}(0)$ is the downward shortwave radiant flux density at the canopy top and f_{df} is the fraction of scattered radiation to total radiation. In Eqs. (15) and (16), we assumed that both PAR and NIR are half of $R_{\mathrm{s}}^{\mathrm{d}}(0)$. According to Goudriaan and van Laar (1994), f_{df} is given as a function of the transmissivity of atmosphere (τ_{atm}) as follows:

$$f_{\mathrm{df}} = \begin{cases} 1 & (\tau_{\mathrm{atm}} < 0.22) \\ 1 - 6.4(\tau_{\mathrm{atm}} - 0.22)^2 & (0.22 \leq \tau_{\mathrm{atm}} < 0.35), \\ 1.47 - 1.66\tau_{\mathrm{atm}} & (\text{otherwise}) \end{cases} \tag{17}$$

$$\tau_{\mathrm{atm}} = R_{\mathrm{s}}^{\mathrm{d}}(0)\sec(\theta)/R_{\mathrm{ex}}, \tag{18}$$

$$R_{\mathrm{ex}} = R_{\mathrm{sun}}(1 + 0.033)\cos(2\pi(D_{\mathrm{oy}}/365)), \tag{19}$$

where R_{ex} is the extraterrestrial radiation, R_{sun} is the solar constant, and D_{oy} is the number of days from 1 January. The Eqs. (15)–(19) that calculate $D_i^{\mathrm{d}}(0)$ are based on formulations by Goudriaan and van Laar (1994), while the original MATSIRO uses different equations.

The transmissivity of canopies for shortwave radiation (τ_{cs}) is expressed as

$$\tau_{\mathrm{cs}} = R_{\mathrm{s}}^{\mathrm{d}}(L)/\left(R_{\mathrm{s}}^{\mathrm{d}}(0) - R_{\mathrm{s}}^{\mathrm{u}}(0)\right). \tag{20}$$

Here, $R_{\mathrm{s}}^{\mathrm{u}}(0)$ and $R_{\mathrm{s}}^{\mathrm{d}}(L)$ are the radiant flux density for upward shortwave at the canopy top and downward shortwave at the bottom of the canopy, respectively. L denotes the LAI, which is calculated in the CGM (Sect. 4.4). $R_{\mathrm{s}}^{\mathrm{u}}(0)$ and $R_{\mathrm{s}}^{\mathrm{d}}(L)$ are represented by

$$R_{\mathrm{s}}^{\mathrm{u}}(0) = r_{11}D_1^{\mathrm{d}}(0) + r_{21}D_2^{\mathrm{d}}(0) + r_{12}S_1^{\mathrm{d}}(0) + r_{22}S_2^{\mathrm{d}}(0), \tag{21}$$

$$R_{\mathrm{s}}^{\mathrm{d}}(L) = \tau_{11}D_1^{\mathrm{d}}(0) + \tau_{21}D_2^{\mathrm{d}}(0) + \tau_{12}S_1^{\mathrm{d}}(0) + \tau_{22}S_2^{\mathrm{d}}(0), \tag{22}$$

where r_{ij} and τ_{ij} are the canopy reflectivity and transmissivity, respectively, and i and j represent wavebands ($i = 1$: PAR; $i = 2$: NIR) and direct ($j = 1$) or scattered radiation ($j = 2$). These are given in Appendix D.

Last, the transmissivity of a canopy for longwave radiation (τ_{cl}) is expressed as

$$\tau_{\mathrm{cl}} = \exp(-FLd_{\mathrm{f}}), \tag{23}$$

where d_{f} is the scattered factor. We set $d_{\mathrm{f}} = \sec(2\pi(53/360))$ from assumption 3 described above.

3.3 Bulk transfer coefficient for latent and sensible heat

This module calculates BTCs for latent and sensible heat ($C_{E_{\mathrm{c}}}$, $C_{E_{\mathrm{g}}}$, $C_{H_{\mathrm{c}}}$, and $C_{H_{\mathrm{g}}}$). The BTCs are used to simulate energy balance (Sect. 3.1). This module is based on Watanabe (1994), where $C_{E_{\mathrm{g}}}$, $C_{E_{\mathrm{c}}}$, $C_{H_{\mathrm{g}}}$, and $C_{H_{\mathrm{c}}}$ are given by

$$C_{E_{\mathrm{g}}} = \left[1/C_{H_{\mathrm{g}}} + r_{\mathrm{s}}U\right]^{-1}, \tag{24}$$

$$C_{E_{\mathrm{c}}} = C_E - C_{E_{\mathrm{g}}}, \tag{25}$$

$$\begin{aligned} C_{H_{\mathrm{g}}} =& \kappa^2\left[\ln\left(\frac{z_{\mathrm{a}} - d}{z_{M\mathrm{g}}}\right) + \Psi_M(\zeta_{\mathrm{g}})\right]^{-1}\left[\ln\left(\frac{z_{\mathrm{a}} - d}{z_{T\mathrm{g}}}\right)\right. \\ & \left. + \Psi_H(\zeta_{\mathrm{g}})\right]^{-1}, \end{aligned} \tag{26}$$

$$C_{H_{\mathrm{c}}} = C_H - C_{H_{\mathrm{g}}}, \tag{27}$$

where C_E and C_H are the BTCs for latent and sensible heat between the entire surface (canopy plus surface) and atmosphere, and are given by

$$\begin{aligned} C_E =& \kappa^2\left[\ln\left(\frac{z_{\mathrm{a}} - d}{z_M}\right) + \Psi_M(\zeta)\right]^{-1}\left[\ln\left(\frac{z_{\mathrm{a}} - d}{z_Q}\right)\right. \\ & \left. + \Psi_E(\zeta)\right]^{-1}, \end{aligned} \tag{28}$$

$$\begin{aligned} C_H =& \kappa^2\left[\ln\left(\frac{z_{\mathrm{a}} - d}{z_M}\right) + \Psi_M(\zeta)\right]^{-1}\left[\ln\left(\frac{z_{\mathrm{a}} - d}{z_T}\right)\right. \\ & \left. + \Psi_H(\zeta)\right]^{-1}. \end{aligned} \tag{29}$$

In Eqs. (24)–(29), κ is the Karman constant; d is the zero-plane displacement height; z_{a} is the reference height at which wind velocity is observed; $z_{M\mathrm{g}}$ and $z_{T\mathrm{g}}$ are the roughness lengths that express the effect of surface on the profiles of momentum and temperature, respectively; z_M, z_T, and z_Q are the roughness lengths of an entire surface (canopy plus surface) for the profiles of momentum, temperature, and specific humidity, respectively; and r_{s} is resistance of topsoil to evaporation. z_{a} is a simulation setting parameter (Table 6), and d, z_M, z_T, z_Q, $z_{M\mathrm{g}}$ and $z_{T\mathrm{g}}$ are the functions of crop height and LAI (Appendix E). r_{s} is given by

$$r_{\mathrm{s}} = 800\left(1 - w_{\mathrm{s}}(0)/w_{\mathrm{sat}}\right)/\left(0.2 + w_{\mathrm{s}}(0)/w_{\mathrm{sat}}\right), \tag{30}$$

where $w_{\mathrm{s}}(0)$ is the water content of topsoil and is calculated in Eq. (53), and w_{sat} is the soil water content at saturation and is a soil-type specific parameter. Ψ_M, Ψ_H, and

Ψ_E are the diabatic correction factors for momentum, heat, and vapour transport, respectively. The factors are functions of atmospheric stability ζ as follows:

$$\Psi_M(\zeta)=\begin{cases}6\ln(1+\zeta) \\ \quad(\zeta>0:\text{stable}) \\ -1.2\ln\left[\frac{1+(1-16\zeta)^{1/2}}{2}\right] \\ \quad(\text{otherwise: unstable}),\end{cases} \tag{31}$$

$$\Psi_H(\zeta)=\Psi_E(\zeta)=\begin{cases}6\ln(1+\zeta) \\ \quad(\zeta>0:\text{stable}) \\ -2\ln\left[\frac{1+(1-16\zeta)^{1/2}}{2}\right] \\ \quad(\text{otherwise: stable}).\end{cases} \tag{32}$$

The equations above are adopted from Campbell and Norman (1998), whereas the original MATSIRO model employs different equations. The variable ζ is replaced by either the atmospheric stability between the entire surface and atmosphere (ζ) or the atmospheric stability between surface and atmosphere (ζ_g). These are given by

$$\zeta=\frac{z_a-d}{L_{MO}}, \tag{33}$$

$$\zeta_g=\frac{z_a-d}{L_{MOg}}, \tag{34}$$

where L_{MO} and L_{MOg} are the Monin–Obukhov lengths for the exchange between the entire surface and atmosphere and between the surface and atmosphere, respectively, and are given by

$$L_{MO}=\frac{\Theta_0 C_M^{3/2}U^2}{\kappa g\{C_{H_g}(T_g-T_a)+C_{H_c}(T_c-T_a)\}}, \tag{35}$$

$$L_{MOg}=\frac{\Theta_0 C_{Mg}^{3/2}U^2}{\kappa g C_{H_g}(T_g-T_a)}, \tag{36}$$

where g is the gravitational constant, T_g and T_c are the temperatures of the surface and canopy, Θ_0 is the potential temperature, C_M and C_{Mg} are the BTC for momentum between an entire surface and atmosphere and between surface and atmosphere, respectively. C_{Mg} in Eq. (36) is introduced according to Maruyama and Kuwagata (2008), while the original MATSIRO uses C_M. T_g and T_c are calculated in Sect. 3.1. Θ_0 is given by

$$\Theta_0=T_a\times(1.0\times10^5/P_a)^{(R_{dry}/c_{pa})}, \tag{37}$$

where R_{dry} is the gas constant of dry air. Although the original MATSIRO fixes Θ_0 at 300 K, MATCRO calculates the value according to Campbell and Norman (1998). C_M and C_{Mg} are given by

$$C_M=k^2\left[\ln\left(\frac{z_a-d}{z_M}\right)+\Psi_M(\zeta)\right]^{-2}, \tag{38}$$

$$C_{Mg}=k^2\left[\ln\left(\frac{z_a-d}{z_{Mg}}\right)+\Psi_M(\zeta_g)\right]^{-2}. \tag{39}$$

Now we have six independent equations, Eqs. (24), (25), (26), (27), (38), and (39), for six unknown variables, C_{E_g}, C_{E_c}, C_{H_g}, C_{H_c}, C_M, and C_{Mg}, respectively. Therefore, we can determine the values of these variables by numerically solving Eqs. (24)–(39). The numerical method is described in Masutomi et al. (2016).

3.4 Canopy water balance

The main purpose of this module is to calculate the fraction of wet canopy (f_{cw}) which is used for simulating energy balance at canopy (Sect. 3.1). To calculate f_{cw}, this module calculates water balance at canopy. Although the module is based on the original MATSIRO, the amount of water that canopies can hold was replaced by using the method described in Penning de Vries et al. (1989). The variable f_{cw} is given as

$$f_{cw}=w_c/w_{cap}, \tag{40}$$

where w_c is the amount of water stored in canopy and w_{cap} is the water capacity of the canopy. The w_c is calculated by solving the canopy water balance, which is given by

$$\rho_w\frac{dw_c}{dt}=I_c-D_g-E_c, \tag{41}$$

where ρ_w is the density of water, I_c is the amount of precipitation intercepted by canopy, D_g is the amount of water that falls from the canopy onto surface due to gravity, and E_c is the amount of water that evaporates from the canopy (Eq. 7). I_c depends on the amount of precipitation (P_r) and LAI (L) and is given by

$$I_c=f_{int}P_r, \tag{42}$$

$$f_{int}=\begin{cases}L & (L<1), \\ 1 & (\text{otherwise}),\end{cases} \tag{43}$$

where f_{int} indicates the interception efficiency of precipitation by canopy. According to Rutter et al. (1975) and Penning de Vries et al. (1989), D_g and w_{cap} are given as

$$D_g=\rho_w D_1\exp(D_2 w_c), \tag{44}$$

$$w_{cap}=(W_{sh}\times10^{-4})/\rho_w, \tag{45}$$

respectively, where D_1 and D_2 are parameters (Rutter et al., 1975), and W_{sh} is the shoot dry weight, which is calculated in the CGM (Eq. 136). In the case of non-flooded surface, the amount of water that falls from the canopy onto soil surface, F_c, is calculated by

$$F_c=D_g+(1-f_{int})P_r+\max\{0,w_c-w_{cap}\}\rho_w/\delta t, \quad (\text{unflooded}) \tag{46}$$

where δt is the time resolution of simulations. In the case of flooded surface, F_c is not calculated because surface water is present. The maximum evaporation from the canopy ($E_{c,\max}$) is given by

$$E_{c,\max} = w_c \rho_w / \delta t. \tag{47}$$

3.5 Soil water and heat transfer

This module calculates heat and water transfer in soil. The main role of this module is to determine the temperature at a soil surface ($T_s(0)$), which is used for simulating energy balance of the surface (Sect. 3.1). Although this module is based on the original MATSIRO, the calculations of the surface and base runoffs are simplified because hydrological calculations are not the main purpose of MATCRO-Rice.

Soil temperature at a soil depth of z from the soil surface ($T_s(z)$) is calculated from the gradient of heat flux in the soil as follows:

$$c_{hs}(z)\frac{\partial T_s(z)}{\partial t} = \frac{\partial G_s(z)}{\partial z}, \tag{48}$$

where c_{hs} is the volumetric heat capacity of the soil and $G_s(z)$ is the heat flux at a soil depth of z and is given from the gradient of soil temperature as

$$G_s(z) = \begin{cases} k_{ts}(z)\frac{\partial T_s(z)}{\partial z} & (0 \le z < z_{\max}) \\ 0 & (z = z_{\max}). \end{cases} \tag{49}$$

Here, k_{ts} is the soil thermal conductivity. In Eq. (49), we assumed that heat flux at the bottom of the soil layer ($z = z_{\max}$) is zero. $z_{\max}$ is a simulation setting parameter. When solving Eqs. (48) and (49), the heat flux from surface to soil (G_{gs}), calculated in Eq. (10), is used as a boundary condition. The parameter c_{hs} is calculated from the heat capacities of soil components as follows:

$$c_{hs}(z) = \rho_s c_{pm} + \rho_w c_{pw} w_s(z), \tag{50}$$

where ρ_s is the bulk density of soil, c_{pm} is the specific heat of soil minerals, and $w_s(z)$ is the volumetric concentration of soil water. ρ_s is a soil-type specific parameter determined by soil type at a simulation site, and c_{pm} is given according to Campbell and Norman (1998). We note that the first term of the right hand side in Eq. (50) indicates the heat capacity of dry soil. Although the original MATSIRO model assigns a default value to the heat capacity of dry soil for all soil types, MATCRO-Rice calculates the value of the heat capacity of dry soil using the bulk density of soil and the heat capacity of soil minerals, as shown in the first term of Eq. (50). It should be noted that the effect of soil organic matter on c_{hs} is not considered in MATCRO. The parameter $k_{ts}(z)$ in Eq. (49) is given by

$$k_{ts}(z) = K_e(z)(k_{tss} - k_{ts0}) + k_{ts0}, \tag{51}$$

$$K_e(z) = \begin{cases} \log(w_s(z)/w_{sat}) + 1.0 & (\text{if } w_s(z)/w_{sat} \ge 0), \\ 0 & (\text{otherwise}) \end{cases} \tag{52}$$

where k_{ts0} and k_{tss} are the thermal conductivity of dry and saturated soils, respectively, K_e is the Kersten number, and w_{sat} is the volumetric soil water concentration at saturation. k_{ts0} and k_{tss} are parameters. We set $k_{ts0} = 0.25$ (Campbell and Norman, 1998) and $k_{tss} = 1.58$ (Best et al., 2011). The parameter w_{sat} is specific to soil type. Equations (51) and (52) for the calculation of $k_{ts}(z)$ are based on the equations developed by Best et al. (2011), while the original MATSIRO employs a different equation. The variable $w_s(z)$ depends on the gradient of water flux and absorption by roots at a soil depth z. In addition, water flux from the canopy layer is added into the top layer of the soil ($0 \le z < z_t$) in the case of non-flooded surface. The variable $w_s(z)$ is given by

$$\frac{\partial w_s(z)}{\partial t} = \begin{cases} \frac{\partial F_s(z)}{\partial z} - S_s(z) + F_c & (0 \le z < z_t), \\ \frac{\partial F_s(z)}{\partial z} - S_s(z) & (z_t < z \le z_b), \end{cases} \tag{53}$$

where $F_s(z)$ and $S_s(z)$ are water flux and absorption by roots at a soil depth of z, respectively. F_c is water flux from the canopy layer (Eq. 46). In the case of flooded surface, the topsoil layer is assumed to be saturated as follows:

$$w_s(z) = w_{sat} \;\; (\text{if flooded}; 0 \le z < z_t). \tag{54}$$

This assumption is not considered in the original MATSIRO. z_t is a simulation setting parameter. $F_s(z)$ is calculated from the gradient of water potentials as follows:

$$F_s(z) = \begin{cases} -K(z)\left(\frac{\partial \psi(z)}{\partial z} + 1\right) & (0 \le z \le z_b), \\ (w_{sat}/\tau_b)\,(w_s(z)/w_{sat})^2 & (z_b < z \le z_{\max}), \end{cases} \tag{55}$$

where $K(z)$ is the hydraulic conductivity and $\psi(z)$ is the water potential at a soil depth of z. $F_s(z)$ in the bottommost layer ($z_b < z < z_{\max}$) represents the base flow, and τ_b is the recession constant for base flow. This model uses a simple model for simulating base flow developed by Hanasaki et al. (2008), although the original MATSIRO utilizes a more complicated model (TOPMODEL: Beven and Kirkby, 1979). z_b is a simulation setting parameter, and τ_b is determined as described in Hanasaki et al. (2008). $K(z)$ and $\psi(z)$ are given by Clapp and Hornberger (1978) as follows:

$$K(z) = K_s\left(\frac{w_s(z)}{w_{sat}}\right)^{2B+3}, \tag{56}$$

$$\psi(z) = \psi_s\left(\frac{w_s(z)}{w_{sat}}\right)^{-B}, \tag{57}$$

where K_s and ψ_s are hydraulic conductivity and water potentials at saturation, respectively, and B is a parameter that determines the relationship of hydraulic conductivity or water potentials between saturated and unsaturated soils. K_s, ψ_s, and B are soil-type specific parameters. $S_s(z)$ in Eq. (53) is calculated from the transpiration

$$S_s(z) = \begin{cases} (E_t/\rho_w)\, f_r(z) & (0 \le z \le z_{rt}), \\ 0 & (z_{rt} < z \le z_{\max}) \end{cases} \tag{58}$$

where E_t is the transpiration calculated in Eq. (8), z_rt is a root depth calculated by the CGM (Eq. 140), $f_\mathrm{r}(z)$ is the distribution of the root and is given by

$$f_\mathrm{r}(z) = (3/2)(z_\mathrm{rt}^2 - z^2)/z_\mathrm{rt}^3, \tag{59}$$

where we assumed that the root has no spatial orientation and is equally distributed in soil. We note that the root depth and distribution in MATCRO changes, although those variables are fixed in the original MATSIRO. The humidity of topsoil, h_ms, used in Eq. (9) is given by

$$h_\mathrm{ms} = \exp(\psi(0)g/(R_\mathrm{a}T_\mathrm{s}(0)). \tag{60}$$

In MATCRO, it is assumed that crops can use soil water beyond the wilting point with water potential of -1500 kPa (w_wlt). Hence, the maximum transpiration ($E_\mathrm{t,max}$) is given by

$$E_\mathrm{t,max} = \frac{\rho_\mathrm{w}}{\delta t}\int_0^{z_\mathrm{rt}} (w_\mathrm{s}(z) - w_\mathrm{wlt})\,\mathrm{d}z, \tag{61}$$

where w_wlt is a soil-type specific parameter, and δt is the time resolution of simulations. In the case of non-flooded surface, evaporation from the surface (E_g) is limited by soil water in the topsoil layer ($0 \leq z < z_\mathrm{t}$) and is given by

$$E_\mathrm{g,max} = \frac{\rho_\mathrm{w}}{\delta t}\int_0^{z_\mathrm{t}} (w_\mathrm{s}(z))\,\mathrm{d}z. \tag{62}$$

In the case of flooded surface, there is no limitation for $E_\mathrm{g,max}$.

4 Crop growth model

The main purpose of the CGM is to simulate rice yield and biomass growth for each organ during a growing period. The CGM has four modules: net carbon assimilation, crop development, crop growth, and LAI, crop height, and root depth. Each module is described in detail in the following sections.

4.1 Net carbon assimilation

The main role of this module is to calculate net carbon assimilation (A_n) in canopy for simulating crop growth. In addition, the stomatal conductance per unit leaf area for both sides of the leave ($\overline{g}_\mathrm{s}$) is calculated for simulating roughness length (Appendix E). Although this module is based on the big-leaf model (Sellers et al., 1992, 1996a) used in the original MATSIRO, we refined two points in the calculation according to the approach described by de Pury and Farquhar (1997) and Dai et al. (2004). The first refinement is that leaves in a canopy are divided into sunlit and shade leaves. Subsequently, A_n per unit leaf area for each the sunlit and shade leaves are calculated. The second refinement is that A_n for the entire canopy is calculated considering vertical distribution of nitrogen within the canopy.

A_n for the entire canopy is given by

$$A_\mathrm{n} = \overline{A}_\mathrm{n,sn}L_\mathrm{sn} + \overline{A}_\mathrm{n,sh}L_\mathrm{sh}, \tag{63}$$

where $\overline{A}_\mathrm{n,sn}$ and $\overline{A}_\mathrm{n,sh}$ are net carbon assimilation per unit leaf area for sunlit and shade leaves, respectively, L_sn and L_sh are LAI for sunlit and shade leaves, respectively, and overbars represent the amounts per unit leaf area. $\overline{A}_\mathrm{n,sn}$ and $\overline{A}_\mathrm{n,sh}$ are defined by the difference between gross carbon assimilation and respiration as follows:

$$\overline{A}_{\mathrm{n},x} = \overline{A}_{\mathrm{g},x} - \overline{R}_{\mathrm{d},x}, \tag{64}$$

where $\overline{A}_{\mathrm{g},x}$ and $\overline{R}_{\mathrm{d},x}$ are gross carbon assimilation and respiration per unit leaf area, respectively, and the suffix x indicates sn or sh. L_sn and L_sh are given as follows:

$$L_\mathrm{sn} = \int_0^L f_\mathrm{sn}(l)\mathrm{d}l, \tag{65}$$

$$L_\mathrm{sh} = \int_0^L (1 - f_\mathrm{sn}(l))\mathrm{d}l, \tag{66}$$

where $f_\mathrm{sn}(l)$ is the fraction of sunlit leaves at a LAI depth of l and is defined as follows:

$$f_\mathrm{sn}(l) = \exp(-Fl\sec(\theta)), \tag{67}$$

where F denotes distribution of leaf orientation and θ is a zenith angle of the sun (Appendix B). The effect of photosynthesis down-regulation due to acclimatization to elevated $\mathrm{CO_2}$ is represented as follows:

$$\overline{A}_{\mathrm{g},x} = f_\mathrm{dwn}\overline{A}_{\mathrm{g}',x}, \tag{68}$$

$$f_\mathrm{dwn} = \{1 + \gamma_\mathrm{gd}\ln(C_\mathrm{a,ppm}/C_0)\}/\{1 + \gamma_\mathrm{g}\ln(C_\mathrm{a,ppm}/C_0)\}, \tag{69}$$

where $\overline{A}_{\mathrm{g}',x}$ is gross carbon assimilation per unit leaf area for sunlit and shade leaves without photosynthesis down-regulation, f_dwn is the factor for photosynthesis down-regulation, γ_gd and γ_g are parameters that characterize the response to increased $\mathrm{CO_2}$, $C_\mathrm{a,ppm}$ is atmospheric $\mathrm{CO_2}$ concentration, and C_0 is the base concentration of $\mathrm{CO_2}$. The Eqs. (68) and (69) are based on Arora et al. (2009), although the original MATSIRO does not consider the effect of photosynthesis down-regulation. We set $\gamma_\mathrm{gd} = 0.42$, $\gamma_\mathrm{g} = 0.9$, and $C_0 = 288$ according to Arora et al. (2009). It should be noted that we have tentatively set these values for the parameters of photosynthesis down-regulation, using the mean values in Arora et al. (2009), because these values are not available for rice. If these values are quantified, they should be replaced. The calculation for $\overline{A}_{\mathrm{g}',x}$ and $\overline{R}_{\mathrm{d},x}$ is based on the leaf photosynthesis model developed by Collatz et al. (1991).

In their model, $\overline{A}_{g',x}$ is determined by three limiting factors: RuBisCO, light, and sucrose synthesis as follows:

$$\overline{A}_{g',x} \leq \min(\overline{\omega}_{c,x}, \overline{\omega}_{e,x}, \overline{\omega}_{s,x}), \tag{70}$$

where $\overline{\omega}_{c,x}$, $\overline{\omega}_{e,x}$, and $\overline{\omega}_{s,x}$ are RuBisCO-limited, light-limited, and sucrose-limited carbon assimilation per unit leaf area, respectively. To implement smooth transition between each limited state, $\overline{A}_{g',x}$ is determined practically by solving the following two equations (Sellers et al., 1996b):

$$\beta_{ce}\overline{\omega}^2_{p,x} - \overline{\omega}^2_{p,x}(\overline{\omega}^2_{c,x} + \overline{\omega}^2_{e,x}) + \overline{\omega}^2_{c,x}\overline{\omega}^2_{e,x} = 0 \tag{71}$$

$$\beta_{ps}\overline{A}^2_{g',x} - \overline{A}^2_{g',x}(\overline{\omega}^2_{p,x} + \overline{\omega}^2_{s,x}) + \overline{\omega}^2_{p,x}\overline{\omega}^2_{s,x} = 0, \tag{72}$$

where β_{ce} and β_{pc} are the parameters that determine the smoothness of transition between each limited state. β_{ce} is a crop-specific parameter and β_{pc} is a parameter that does not depend on crop type. The variables $\overline{\omega}_{c,x}$, $\overline{\omega}_{e,x}$, and $\overline{\omega}_{s,x}$ are given by

$$\overline{\omega}_{c,x} = \overline{V}_{mc,x}\left\{\frac{c_{i,x} - \Gamma^*}{c_{i,x} + K_c(1 + [O_2]/K_O)}\right\} \tag{73}$$

$$\overline{\omega}_{e,x} = \epsilon_e \overline{Q}_x \left\{\frac{c_{i,x} + \Gamma^*}{c_{i,x} + 2\Gamma^*}\right\} \tag{74}$$

$$\overline{\omega}_{s,x} = \overline{V}_{ms,x}/2. \tag{75}$$

Here, $\overline{V}_{mc,x}$ and $\overline{V}_{ms,x}$ are the maximum RuBisCO capacity per unit leaf area for $\overline{\omega}_{c,x}$ and $\overline{\omega}_{s,x}$, respectively, $c_{i,x}$ is the partial pressure of intercellular CO_2, $[O_2]$ is the partial pressure of intercellular O_2, $\overline{Q}_x$ is the photon flux density for PAR absorbed per unit leaf area by sunlit and shade leaves, ϵ_e is the quantum efficiency, Γ^* is the light compensation point, and K_c and K_O are the Michaelis constant for CO_2 fixation and oxygen inhibition, respectively. We set $[O_2] = 20\,900$ (Collatz et al., 1991). ϵ_e is a crop-specific parameter. $\overline{V}_{mc,x}$ and $\overline{V}_{ms,x}$ are given by

$$\overline{V}_{mc,x} = \overline{V}_{max,x} f_v \left[2^{q_t}/\{1 + \exp(s_1(T_c - s_2))\}\right], \tag{76}$$

$$\overline{V}_{ms,x} = \overline{V}_{max,x} f_v \left[2^{q_t}/\{1 + \exp(s_3(s_4 - T_c))\}\right], \tag{77}$$

where $\overline{V}_{max,x}$ is the reference value for the maximum RuBisCO capacity per unit leaf area of sunlit ($\overline{V}_{max,sn}$) and shade ($\overline{V}_{max,sh}$) leaves; f_v is the water stress factor; s_1, s_2, s_3, and s_4 are parameters that represent temperature dependence of $\overline{V}_{max,x}$ on $\overline{V}_{mc,x}$ or $\overline{V}_{ms,x}$; and q_t is a function that represents temperature dependency. The variables s_1 and s_2 are parameterized in Masutomi et al. (2016), whereas s_3 is a parameter that does not depend on crop type and s_4 is a crop-specific parameter. f_v is given by

$$f_v = \int_0^{r_t} f_r(z) f_s(z) \mathrm{d}z, \tag{78}$$

$$f_s(z) = \frac{2}{1 + \exp(-\gamma_s \psi_s(z))}, \tag{79}$$

where $f(z)$ is the water stress function on photosynthesis at a soil depth of z, and γ_s is a crop-specific parameter for water stress on photosynthesis. Equation (79) is based on Bouman et al. (2001), although the original MATSIRO uses a different equation. q_t is given by

$$q_t = (T_c - 298)/10. \tag{80}$$

$\overline{V}_{max,sn}$ and $\overline{V}_{max,sh}$ are defined by

$$\overline{V}_{max,sn} = \left(\int_0^L V_{max}(l) f_{sn}(l) \mathrm{d}l\right)/L_{sn}, \tag{81}$$

$$\overline{V}_{max,sh} = \left(\int_0^L V_{max}(l)(1 - f_{sn}(l)) \mathrm{d}l\right)/L_{sh}, \tag{82}$$

where $V_{max}(l)$ is the reference value for the maximum RuBisCO capacity at a LAI depth of l. The vertical distribution of $V_{max}(l)$ depends on that of leaf nitrogen within the canopy and is given by

$$V_{max}(l) = V_{max}(0)\exp(-K_n l), \tag{83}$$

where K_n is a parameter that represents the vertical distribution of leaf nitrogen, and $V_{max}(0)$ is the reference value for the maximum RuBisCO capacity at the canopy top. $V_{max}(0)$ as well as s_1 and s_2 are parameterized in Masutomi et al. (2016), and we set $K_n = 0.3$ (Oleson and Lawrence, 2013). Γ^*, K_c, and K_O are given by

$$\Gamma^* = 0.5[O_2]/S, \tag{84}$$

$$K_c = 30 \times 2.1^{q_t}, \tag{85}$$

$$K_O = 30000 \times 1.2^{q_t}, \tag{86}$$

$$S = 2600 \times 0.57^{q_t}, \tag{87}$$

where S is the ratio of the partition of RuBP to the carboxylase or oxygenase reactions of RuBisCO.

$\overline{Q}_x$ in Eq. (74) is defined by the following equation:

$$\overline{Q}_x = Q_x/L_x. \tag{88}$$

Here, Q_x is the PAR absorbed by the entire canopy for sunlit (Q_{sn}) and shade (Q_{sh}) leaves. Q_{sn} and Q_{sh} consist of direct and scattered components and are given as

$$Q_{sn} = Q_{sn,d} + Q_{sn,s}, \tag{89}$$

$$Q_{sh} = Q_{sh,s}, \tag{90}$$

where $Q_{sn,d}$, $Q_{sn,s}$, and $Q_{sh,s}$ are the direct PAR absorbed by sunlit leaves, the scattered PAR absorbed by sunlit leaves, and the scattered PAR absorbed by shade leaves, respectively. These are described by

$$Q_{sn,d} = k_q \int_0^L \frac{\mathrm{d}D_1^d(l)}{\mathrm{d}l}\mathrm{d}l, \tag{91}$$

$$Q_{\mathrm{sn,s}} = k_{\mathrm{q}} \int_{0}^{L} \frac{\mathrm{d}(S_1^{\mathrm{d}}(l) - S_1^{\mathrm{u}}(l))}{\mathrm{d}l} f_{\mathrm{sn}}(l)\mathrm{d}l, \tag{92}$$

$$Q_{\mathrm{sh,s}} = k_{\mathrm{q}} \int_{0}^{L} \frac{\mathrm{d}(S_1^{\mathrm{d}}(l) - S_1^{\mathrm{u}}(l))}{\mathrm{d}l} (1 - f_{\mathrm{sn}}(l))\mathrm{d}l, \tag{93}$$

where $D_1^{\mathrm{d}}(l)$, $S_1^{\mathrm{d}}(l)$, and $S_1^{\mathrm{u}}(l)$ are calculated by the LSM (Eqs. 12–14) and k_{q} is a constant that transfers the radiant flux density to photon flux density.

$\overline{R}_{\mathrm{d},x}$ in Eq. (64) is given by the following equation:

$$\overline{R}_{\mathrm{d},x} = f_{\mathrm{d}} \overline{V}_{\mathrm{max},x} \left[2^{q_t} / \{1 + \exp(s_5(T_{\mathrm{c}} - s_6))\}\right], \tag{94}$$

where f_{d} is a respiration factor and crop-specific parameter, whereas s_5 and s_6 are parameters that are not crop dependent. It should be noted that $\overline{A}_{\mathrm{n},x}$ can be calculated using the equations described in this section (Eqs. 64–94) if $c_{\mathrm{i},x}$ is given.

$\overline{A}_{\mathrm{n},x}$ should be equal to the CO_2 flux between the leaf interior and boundary layer and the CO_2 flux between the leaf boundary layer and the atmosphere. If these requirements are fulfilled, the following equation can be derived:

$$\begin{aligned} \overline{A}_{\mathrm{n},x} &= (\overline{g}_{\mathrm{l}}/P_{\mathrm{a}})(c_{\mathrm{a}} - c_{\mathrm{s},x})/1.4 \\ &= (\overline{g}_{\mathrm{st},x}/P_{\mathrm{a}})(c_{\mathrm{s},x} - c_{\mathrm{i},x})/1.6, \end{aligned} \tag{95}$$

where c_{a} is the partial pressure of atmospheric CO_2, $c_{\mathrm{s},x}$ is the partial pressure of CO_2 at the leaf boundary layer for sunlit and shade leaves, $\overline{g}_{\mathrm{l}}$ is the leaf boundary conductance for vapour per unit leaf area, and $\overline{g}_{\mathrm{st},x}$ is the stomatal conductance for vapour per unit leaf area for sunlit and shade leaves. From Eq. (95), $c_{\mathrm{i},x}$ and $c_{\mathrm{s},x}$ are defined by

$$c_{\mathrm{i},x} = c_{\mathrm{a}} - (1.4/\overline{g}_{\mathrm{l}} + 1.6/\overline{g}_{\mathrm{st},x})\overline{A}_{\mathrm{n},x} P_{\mathrm{a}}, \tag{96}$$

$$c_{\mathrm{s},x} = c_{\mathrm{a}} - 1.4\overline{A}_{\mathrm{n},x} P_{\mathrm{a}}/\overline{g}_{\mathrm{l}}. \tag{97}$$

The variables c_{a} and $\overline{g}_{\mathrm{l}}$ are given by

$$c_{\mathrm{a}} = (C_{\mathrm{a,ppm}} \times 10^{-6}) P_{\mathrm{a}}, \tag{98}$$

$$\overline{g}_{\mathrm{l}} = (\overline{g}_{\mathrm{a}}/2) \times P_{\mathrm{a}}/(T_{\mathrm{c}} R_{\mathrm{vap}} \omega_{\mathrm{H_2O}}), \tag{99}$$

$$\overline{g}_{\mathrm{a}} = c_{\mathrm{h}} U_{\mathrm{c}}, \tag{100}$$

where $w_{\mathrm{H_2O}}$ is a constant for the molar weight of vapour, $\overline{g}_{\mathrm{a}}$ is the leaf boundary conductance for heat per unit leaf area (for both sides of the leaf), c_{h} is the leaf transfer coefficient for heat and is a crop-specific parameter, and U_{c} is the mean wind speed in the canopy (Appendix F). Note that Eqs. (99) and (100) are based on Maruyama and Kuwagata (2008), whereas the original MATSIRO uses $C_{H_{\mathrm{c}}} U/L$ instead of $\overline{g}_{\mathrm{a}}/2$ in Eq. (99).

$\overline{A}_{\mathrm{n},x}$ meets the Ball–Berry relationship (Ball, 1988), which describes the relationship between $\overline{A}_{\mathrm{n},x}$, $\overline{g}_{\mathrm{st},x}$, and other environmental conditions. The Ball–Berry relationship is given by

$$\overline{g}_{\mathrm{st},x} = \begin{cases} m \frac{\overline{A}_{\mathrm{n},x} P_{\mathrm{a}}}{c_{\mathrm{s},x}} h_{\mathrm{s},x} + b & (\text{if } \overline{A}_{\mathrm{n},x} > 0), \\ b & (\text{otherwise}) \end{cases} \tag{101}$$

where m and b are the slope and intercept of the Ball–Berry relationship, and $h_{\mathrm{s},x}$ is the relative humidity at the leaf boundary. It is noteworthy that b indicates the stomatal conductance when $\overline{A}_{\mathrm{n},x}$ is equal to or less than zero (Baldocchi, 1994) and that the effect of water stress on b is not considered in MATCRO-Rice. The variables m and b are crop-specific parameters, and $h_{\mathrm{s},x}$ is defined by

$$h_{\mathrm{s},x} = e_{\mathrm{s},x}/e_{\mathrm{sat}}(T_{\mathrm{c}}, P_{\mathrm{a}}), \tag{102}$$

where $e_{\mathrm{s},x}$ is the vapour pressure at the leaf boundary and e_{sat} is the saturated vapour pressure. The variable $e_{\mathrm{s},x}$ is expressed as

$$e_{\mathrm{s},x} = (e_{\mathrm{a}}\overline{g}_{\mathrm{l}} + e_{\mathrm{i}}\overline{g}_{\mathrm{st},x})/(\overline{g}_{\mathrm{l}} + \overline{g}_{\mathrm{st},x}), \tag{103}$$

where e_{a} and e_{i} are the vapour pressure in the air and leaf, respectively. Equation (103) is derived from the fact that the water vapour flux from the stomata to the leaf surface is equal to the water vapour flux from the leaf surface into the atmosphere, which is shown in the following equation:

$$\overline{g}_{\mathrm{st},x}(e_{\mathrm{i}} - e_{\mathrm{s},x}) = \overline{g}_{\mathrm{l}}(e_{\mathrm{s},x} - e_{\mathrm{a}}). \tag{104}$$

The parameters e_{a}, e_{i}, and e_{sat} are given by

$$e_{\mathrm{a}} = Q(R_{\mathrm{vap}}/R_{\mathrm{dry}})P_{\mathrm{a}}, \tag{105}$$

$$e_{\mathrm{i}} = e_{\mathrm{sat}}(T_{\mathrm{c}}, P_{\mathrm{a}}), \tag{106}$$

$$e_{\mathrm{sat}}(T_{\mathrm{c}}, P_{\mathrm{a}}) = Q_{\mathrm{sat}}(T_{\mathrm{c}}, P_{\mathrm{a}})(R_{\mathrm{vap}}/R_{\mathrm{dry}})P_{\mathrm{a}}, \tag{107}$$

where e_{i} is assumed to be saturated.

Now we have three relationships (Eqs. 64–94, 96, and 101) in terms of three unknown variables ($\overline{A}_{\mathrm{n},x}$, $c_{\mathrm{i},x}$, and $\overline{g}_{\mathrm{st},x}$). Therefore, we can determine the values for $\overline{A}_{\mathrm{n},x}$, $c_{\mathrm{i},x}$, and $\overline{g}_{\mathrm{st},x}$, by numerically solving the three relationships. The numerical method is described in Masutomi et al. (2016).

Last, $\overline{g}_{\mathrm{s}}$ is given by the following equation:

$$\overline{g}_{\mathrm{s}} = \overline{g}_{\mathrm{st}} \times (T_{\mathrm{c}} R_{\mathrm{vap}} w_{\mathrm{H_2O}}/P_{\mathrm{a}}), \tag{108}$$

$$\overline{g}_{\mathrm{st}} = \{(\overline{g}_{\mathrm{st,sn}} \times L_{\mathrm{sn}} + \overline{g}_{\mathrm{st,sh}} \times L_{\mathrm{sh}})/L\} \times 2, \tag{109}$$

where $\overline{g}_{\mathrm{st}}$ is the stomatal conductance for vapour per unit leaf area for both sides of the leaf.

4.2 Crop development

The crop development module calculates D_{vs}, which is an index used to quantify developmental stage of crops. D_{vs} is mainly used for determining the timing of transplanting, heading, and harvesting. In addition, D_{vs} is used for partitioning of carbon assimilation into each organ and for estimating LAI and height. This module is based on the formulation by Bouman et al. (2001). D_{vs} is calculated from

$$D_{\mathrm{vs}} = G_{\mathrm{ds}}/G_{\mathrm{ds,m}}, \tag{110}$$

$$G_{\mathrm{ds}} = \int_{0}^{t} D_{\mathrm{vr}} \mathrm{d}t', \tag{111}$$

$$D_{\mathrm{vr}} = \begin{cases} 0 & (T_{\mathrm{a}} < T_{\mathrm{b}} | T_{\mathrm{h}} \leq T_{\mathrm{a}}) \\ T_{\mathrm{a}} - T_0 & (T_{\mathrm{b}} \leq T_{\mathrm{a}} < T_{\mathrm{o}}), \\ (T_{\mathrm{o}} - T_{\mathrm{b}})(T_{\mathrm{h}} - T_{\mathrm{a}})/(T_{\mathrm{h}} - T_{\mathrm{o}}) & (T_{\mathrm{o}} \leq T_{\mathrm{a}} < T_{\mathrm{h}}), \end{cases} \tag{112}$$

where G_{ds} is the growing degree seconds at t, $G_{\mathrm{ds,m}}$ is G_{ds} required until maturation, D_{vr} is the development rate at t, T_0 is the melting temperature of water, and T_{b}, T_{h}, and T_{o} are the minimum temperature, maximum temperature, and optimal temperature for development, respectively. The value of $G_{\mathrm{ds,m}}$ is parameterized in Masutomi et al. (2016), and T_{b}, T_{h}, and T_{o} are crop-specific parameters. T_0 is a physical constant (Table 5). It should be noted that $D_{\mathrm{vs}} = 0$ represents sowing and $D_{\mathrm{vs}} = 1$ represents maturation. Furthermore, we introduce two parameters that represent the timing of emergence ($D_{\mathrm{vs,e}}$) and heading ($D_{\mathrm{vs,h}}$). Both $D_{\mathrm{vs,e}}$ and $D_{\mathrm{vs,h}}$ are crop-specific parameters. The values of $D_{\mathrm{vs,e}}$ and $D_{\mathrm{vs,h}}$ are parameterized in Masutomi et al. (2016). Crop simulation start at the day of sowing ($D_{\mathrm{oy,sw}}$) which is a simulation setting parameter.

During the transplantation of rice seedlings, the seedlings enter transplanting shock, which prevents shoot growth (Bouman et al., 2001). In MATCRO-Rice, the transplanting shock period is defined by D_{vs}, where $D_{\mathrm{vs,tr}}$ is D_{vs} at the time when transplanting shock starts and $D_{\mathrm{vs,te}}$ is D_{vs} at which transplanting shock ends. Both $D_{\mathrm{vs,tr}}$ and $D_{\mathrm{vs,te}}$ are parameterized in Masutomi et al. (2016).

4.3 Crop growth

This module calculates the growth of organs and reserves. The organs considered in MATCRO-Rice include the leaf, stem, panicle, and root. In addition, the model considers glucose reserves in leaves and starch reserves in stems. All carbon assimilated in leaves through photosynthesis is first stored in the leaf in the form of glucose. Then, the stored glucose is partitioned to each organ and stored in the stem when the amount of the stored glucose exceeds the critical rate to dry weight of the leaf. This module is based on MACROS (Penning de Vries et al., 1989).

The dry weights of each organ and reserve are expressed by

$$W_{\mathrm{lef}} = W_{\mathrm{lef,0}} + \int_{t_{\mathrm{e}}}^{t} (G_{\mathrm{r,lef}} - L_{\mathrm{s,lef}})\mathrm{d}t', \tag{113}$$

$$W_{\mathrm{stm}} = W_{\mathrm{stm,0}} + \int_{t_{\mathrm{e}}}^{t} G_{\mathrm{r,stm}}\mathrm{d}t', \tag{114}$$

$$W_{\mathrm{pnc}} = \int_{t_{\mathrm{e}}}^{t} G_{\mathrm{r,pnc}}\mathrm{d}t' \tag{115}$$

$$W_{\mathrm{rot}} = W_{\mathrm{rot,0}} + \int_{t_{\mathrm{e}}}^{t} G_{\mathrm{r,rot}}\mathrm{d}t', \tag{116}$$

$$W_{\mathrm{stc}} = \int_{t_{\mathrm{e}}}^{t} (G_{\mathrm{r,stc}} - R_{\mathrm{m,stc}})\mathrm{d}t', \tag{117}$$

$$W_{\mathrm{glu}} = W_{\mathrm{glu,0}} + \int_{t_{\mathrm{e}}}^{t} G_{\mathrm{r,glu}}\mathrm{d}t', \tag{118}$$

where W_{lef}, W_{stm}, W_{pnc}, W_{rot}, W_{stc}, and W_{glu} are the dry weight of leaves, stems, panicles, roots, starch reserves, and glucose reserves at t, respectively; $W_{\mathrm{lef,0}}$, $W_{\mathrm{stm,0}}$, $W_{\mathrm{rot,0}}$, and $W_{\mathrm{glu,0}}$ represent the initial dry weight at emergence of each organ and reserve; $G_{\mathrm{r,lef}}$, $G_{\mathrm{r,stm}}$, $G_{\mathrm{r,pnc}}$, $G_{\mathrm{r,rot}}$, $G_{\mathrm{r,stc}}$, and $G_{\mathrm{r,glu}}$ are the growth rates of the corresponding organ and reserve; $L_{\mathrm{s,lef}}$ is the loss rate of leaves due to leaf death; $R_{\mathrm{m,stc}}$ is the loss rate of starch reserves in the stem due to remobilization; t_{e} is the time at emergence after sowing; and $W_{\mathrm{lef,0}}$, $W_{\mathrm{stm,0}}$, $W_{\mathrm{rot,0}}$, and $W_{\mathrm{glu,0}}$ are simulation setting parameters.

The glucose reserve in the leaf is supplied through photosynthesis in leaves and remobilization from the stem. Thus, the supply of glucose is given by

$$S_{\mathrm{glu}} = A_{\mathrm{n}} C_{\mathrm{CO_2,glu}} + R_{\mathrm{m,stc}} C_{\mathrm{stc,glu}}, \tag{119}$$

where S_{glu} is the supply of glucose to the leaf reserve, A_{n} is the net carbon assimilation calculated in Eq. (63), and $C_{\mathrm{CO_2,glu}}$ and $C_{\mathrm{stc,glu}}$ are the conversion factors from CO_2 or starch to glucose, which are chemically determined (Table 5). We assumed that the partition of glucose in leaves to each organ occurs if the following equation is met:

$$W_{\mathrm{glu}} + S_{\mathrm{glu}}\delta t > k_{\mathrm{glu}} W_{\mathrm{lef}}, \tag{120}$$

where δt is one simulation time step, k_{glu} is the critical ratio at which the partition of glucose happens, and δt is a simulation setting parameter. We set $k_{\mathrm{glu}} = 0.1$ (Penning de Vries et al., 1989). When Eq. (120) is met, the amount of glucose that exceeds the critical ratio is partitioned to each organ and reserve according to the following equation:

$$G_{\mathrm{p,glu}} = (W_{\mathrm{glu}} + S_{\mathrm{glu}}\delta t - k_{\mathrm{glu}} W_{\mathrm{lef}})/\delta t, \tag{121}$$

where $G_{\mathrm{p,glu}}$ is the amount of glucose partitioned to each organ and reserve. The growth rate of each organ and reserve is expressed as follows:

$$G_{\mathrm{r,lef}} = G_{\mathrm{p,glu}} P_{\mathrm{r,sh}} P_{\mathrm{r,lef}} C_{\mathrm{glu,lef}}, \tag{122}$$

$$\begin{aligned} G_{\mathrm{r,stm}} = {} & G_{\mathrm{p,glu}} P_{\mathrm{r,sh}} (1 - P_{\mathrm{r,lef}} - P_{\mathrm{r,pnc}}) \\ & \times (1 - f_{\mathrm{stc}}) C_{\mathrm{glu,stm}}, \end{aligned} \tag{123}$$

$$G_{\mathrm{r,pnc}} = G_{\mathrm{p,glu}} P_{\mathrm{r,sh}} P_{\mathrm{r,pnc}} C_{\mathrm{glu,pnc}}, \tag{124}$$

$$G_{\mathrm{r,rot}} = G_{\mathrm{p,glu}} (1 - P_{\mathrm{r,sh}}) C_{\mathrm{glu,rot}}, \tag{125}$$

$$G_{\mathrm{r,stc}} = G_{\mathrm{p,glu}} P_{\mathrm{r,sh}} (1 - P_{\mathrm{r,lef}} - P_{\mathrm{r,pnc}}) f_{\mathrm{stc}} C_{\mathrm{glu,stc}}, \tag{126}$$

$$G_{\mathrm{r,glu}} = (k_{\mathrm{glu}} W_{\mathrm{lef}} - W_{\mathrm{glu}})/\delta t, \tag{127}$$

where $P_{\mathrm{r,sh}}$ is the ratio of glucose partitioned to the shoot; $P_{\mathrm{r,lef}}$ and $P_{\mathrm{r,pnc}}$ are the partition ratios of glucose from the shoot to the leaf and panicle; f_{stc} is the proportion of glucose allocated to starch reserve in the stem; and $C_{\mathrm{glu,lef}}$, $C_{\mathrm{glu,stm}}$, $C_{\mathrm{glu,rot}}$, $C_{\mathrm{glu,pnc}}$, and $C_{\mathrm{glu,stc}}$ are dry weight of corresponding organs and reserves that are produced from the unit weight of glucose. f_{stc}, $C_{\mathrm{glu,lef}}$, $C_{\mathrm{glu,stm}}$, $C_{\mathrm{glu,rot}}$, and $C_{\mathrm{glu,pnc}}$ are crop-specific parameters. f_{stc} is parameterized in Masutomi et al. (2016). We set the values of $C_{\mathrm{glu,lef}}$, $C_{\mathrm{glu,stm}}$, $C_{\mathrm{glu,rot}}$, and $C_{\mathrm{glu,pnc}}$ according to Penning de Vries et al. (1989). $C_{\mathrm{glu,stc}}$ is a chemical constant. If Eq. (120) is not met, glucose is not partitioned into each organ and reserve, except as the glucose reserve in the leaf. Therefore, the growth rate of each organ and reserve are calculated as follows:

$$G_{\mathrm{r,lef}} = G_{\mathrm{r,stm}} = G_{\mathrm{r,rot}} = G_{\mathrm{r,pnc}} = G_{\mathrm{r,stc}} = 0 \tag{128}$$

$$G_{\mathrm{r,glu}} = S_{\mathrm{glu}}. \tag{129}$$

The partition ratios to each organ are given as

$$P_{\mathrm{r,sh}} = \begin{cases} 1 - P_{\mathrm{rot}} & (D_{\mathrm{vs}} \leq D_{\mathrm{vs,tr}}) \\ 0 & (D_{\mathrm{vs,tr}} < D_{\mathrm{vs}} \leq D_{\mathrm{vs,te}}), \\ 1 - P_{\mathrm{rot}} & (D_{\mathrm{vs,te}} < D_{\mathrm{vs}} \leq D_{\mathrm{vs,rot1}}) \\ \frac{1 - P_{\mathrm{rot}}(D_{\mathrm{vs,rot1}} - D_{\mathrm{vs}})}{(D_{\mathrm{vs,rot2}} - D_{\mathrm{vs,rot1}})} & (D_{\mathrm{vs,rot1}} < D_{\mathrm{vs}} \leq D_{\mathrm{vs,rot2}}) \\ 1 & (\text{otherwise}) \end{cases} \tag{130}$$

$$P_{\mathrm{r,lef}} = \begin{cases} P_{\mathrm{lef}} & (D_{\mathrm{vs}} \leq D_{\mathrm{vs,lef1}}) \\ \frac{P_{\mathrm{lef}}(D_{\mathrm{vs,lef2}} - D_{\mathrm{vs}})}{(D_{\mathrm{vs,lef2}} - D_{\mathrm{vs,lef1}})} & (D_{\mathrm{vs,lef1}} < D_{\mathrm{vs}} \leq D_{\mathrm{vs,lef2}}), \\ 0 & (\text{otherwise}) \end{cases} \tag{131}$$

$$P_{\mathrm{r,pnc}} = \begin{cases} 0 & (D_{\mathrm{vs}} \leq D_{\mathrm{vs,pnc1}}) \\ \frac{(D_{\mathrm{vs}} - D_{\mathrm{vs,pnc1}})}{(D_{\mathrm{vs,pnc2}} - D_{\mathrm{vs,pnc2}})} & (D_{\mathrm{vs,pnc1}} < D_{\mathrm{vs}} \leq D_{\mathrm{vs,pnc2}}), \\ 1 & (\text{otherwise}) \end{cases} \tag{132}$$

where $D_{\mathrm{vs,rot1}}$, $D_{\mathrm{vs,rot2}}$, $D_{\mathrm{vs,lef1}}$, $D_{\mathrm{vs,lef2}}$, $D_{\mathrm{vs,pnc1}}$, and $D_{\mathrm{vs,pnc2}}$ represent the D_{vs} values at which corresponding partitions change; P_{rot} is the ratio of partitioned glucose to the roots at $D_{\mathrm{vs}} < D_{\mathrm{vs,rot1}}$; and P_{lef} is the ratio of glucose partitioned to the leaf and glucose partitioned to the shoot at $D_{\mathrm{vs}} < D_{\mathrm{vs,lef1}}$. $D_{\mathrm{vs,rot1}}$, $D_{\mathrm{vs,rot2}}$, $D_{\mathrm{vs,lef1}}$, $D_{\mathrm{vs,lef2}}$, $D_{\mathrm{vs,pnc1}}$, $D_{\mathrm{vs,pnc2}}$, P_{rot}, and P_{lef} are crop-specific parameters and are parameterized in Masutomi et al. (2016). In Eq. (130), we assume that no glucose is partitioned to the shoot during transplanting shock ($D_{\mathrm{vs,tr}} < D_{\mathrm{vs}} \leq D_{\mathrm{vs,te}}$). It is important to note that transplanting shock is considered only when transplanting is conducted.

Loss of leaf dry weight due to leaf death ($L_{\mathrm{s,lef}}$) and remobilization from starch reserve in the stem ($R_{\mathrm{m,stm}}$) occur after heading and they are defined as follows:

$$L_{\mathrm{s,lef}} = \begin{cases} 0 & (D_{\mathrm{vs}} \leq D_{\mathrm{vs,h}}), \\ r_{\mathrm{dd,lef}}(W_{\mathrm{lef}} + W_{\mathrm{glu}}) & (\text{otherwise}) \end{cases} \tag{133}$$

$$R_{\mathrm{m,stc}} = \begin{cases} 0 & (D_{\mathrm{vs}} \leq D_{\mathrm{vs,h}}), \\ r_{\mathrm{rm,stc}} W_{\mathrm{stc}} & (\text{otherwise}) \end{cases} \tag{134}$$

where $r_{\mathrm{dd,lef}}$ and $r_{\mathrm{rm,stc}}$ represent the ratios of leaf death and remobilization. $r_{\mathrm{dd,lef}}$ varies with D_{vs} as follows:

$$r_{\mathrm{dd,lef}} = r_{\mathrm{d1,lef}}(D_{\mathrm{vs}} - D_{\mathrm{vs,h}})/(1 - D_{\mathrm{vs,h}}), \tag{135}$$

where $r_{\mathrm{d1,lef}}$ is the ratio of leaf death at harvest ($D_{\mathrm{vs}} = 1$) and it is parameterized in Masutomi et al. (2016). We set $r_{\mathrm{rm,stc}} = 1.16 \times 10^{-6}$, assuming that all starch stored in the stem is remobilized in 10 days after heading (Bouman et al., 2001).

Last, the dry weight of the shoot (W_{sh}), used in Sect. 3.4, is given by

$$W_{\mathrm{sh}} = W_{\mathrm{lef}} + W_{\mathrm{stm}} + W_{\mathrm{pnc}} + W_{\mathrm{stc}} + W_{\mathrm{glu}}. \tag{136}$$

4.4 LAI, crop height, and root depth

Leaf area index (L), crop height (h_{gt}), and root depth (z_{rt}) are expressed as

$$L = (W_{\mathrm{lef}} + W_{\mathrm{glu}})/S_{\mathrm{lw}}, \tag{137}$$

$$S_{\mathrm{lw}} = S_{\mathrm{lw,mx}} + \left(S_{\mathrm{lw,mn}} - S_{\mathrm{lw,mx}}\right)\exp\left(-k_{S_{\mathrm{lw}}} D_{\mathrm{vs}}\right), \tag{138}$$

$$h_{\mathrm{gt}} = \begin{cases} h_{\mathrm{aa}} L^{h_{\mathrm{ab}}} & (D_{\mathrm{vs}} < D_{\mathrm{vs,h}}), \\ h_{\mathrm{ba}} L^{h_{\mathrm{bb}}} & (D_{\mathrm{vs,h}} < D_{\mathrm{vs}}) \end{cases} \tag{139}$$

$$z_{\mathrm{rt}} = \min\{z_{\mathrm{rt,mx}}, r_{\mathrm{rt}}(t - t_{\mathrm{e}})\}, \tag{140}$$

where S_{lw} is the specific leaf weight; $S_{\mathrm{lw,mx}}$ and $S_{\mathrm{lw,mn}}$ are the maximum and minimum values of specific leaf weight, respectively; $k_{S_{\mathrm{lw}}}$ is a parameter that determines the relationship between D_{vs} and specific leaf weight; h_{aa}, h_{ab}, h_{ba}, and h_{bb} are parameters that define the relationship between LAI and crop height; $z_{\mathrm{rt,mx}}$ is the maximum root depth; and r_{rt} is the root growth rate. The allometric equations for estimating crop height (Eq. 139) is based on Maruyama and Kuwagata (2010). $S_{\mathrm{lw,mx}}$, $S_{\mathrm{lw,mn}}$, $k_{S_{\mathrm{lw}}}$, h_{aa}, h_{ab}, h_{ba}, and h_{bb} are crop-specific parameters; they are parameterized in Masutomi et al. (2016). $z_{\mathrm{rt,mx}}$ and r_{rt} are also crop-specific parameters, and they are set to $z_{\mathrm{rt,mx}} = 0.3$ and $r_{\mathrm{rt}} = 1.16 \times 10^{-7}$ ($= 0.01\,\mathrm{m\,day^{-1}}$) (Penning de Vries et al., 1989).

4.5 Crop yield

Crop yield is calculated from dry weight of the panicle at maturity as follows:

$$Y_{\mathrm{ld}} = k_{\mathrm{yld}} W_{\mathrm{pnc,mt}}, \tag{141}$$

where Y_{ld} is the crop yield, $W_{\mathrm{pnc,mt}}$ is the dry weight of the panicle at maturity, and k_{yld} is the ratio of the crop yield to $W_{\mathrm{pnc,mt}}$. The variable k_{yld} is a crop-specific parameter and it is parameterized in Masutomi et al. (2016).

5 Concluding remarks

We developed a new LSM-CGM combined model for paddy rice fields called MATCRO-Rice, which is fully described in the present paper. MATCRO-Rice has two features: (i) the model can consistently simulate LHF, SHF, biomass growth for each organ, and crop yield by exchanging variables listed in Table 2; (ii) the model considers water surface and irrigation in paddy rice fields. According to our literature survey, MATCRO-Rice is the first LSM-CGM combined model for rice that employs these two features.

The first feature enables us to apply the model to a wide range of integrated issues. For example, by using MATCRO-Rice, we can assess the impacts of paddy rice fields on climate through heat and water fluxes and consistently assess the impacts of climate on rice productivity. Osborne et al. (2009) showed that the interaction between agricultural land and climate can play an important role in the annual variability of both the climate and crop yield. MATCRO-Rice can investigate the impact of the interactions at paddy rice fields on climate and rice productivity. MATCRO-Rice can be a useful tool for addressing the integrated issues of agriculture and hydrology.

MATCRO-Rice can be also applied to simultaneously assess the climate change impacts on rice productivity and hydrological cycle in paddy rice fields. Masutomi et al. (2009) showed that climate change will have significant impact on rice productivity across Asia. In addition, agricultural land is one of the key players in global hydrological cycle, and climate change will globally alter the hydrological cycle (Oki and Kanae, 2006).

The first feature also gives us a chance to comprehensively evaluate the model with observations (Lei et al., 2010). Model evaluation is described in the companion paper (Masutomi et al., 2016).

The current version (v. 1) of MATCRO-Rice has a major limitation. Nitrogen dynamics is not included in MATCRO-Rice, although it is well known that nitrogen stress significantly affects crop growth, and hence LHF and SHF. This indicates that MATCRO-Rice simulates LHF, SHF, biomass growth, and crop yield with no nitrogen stress. To apply the model to the site with nitrogen stress, it is necessary to include nitrogen dynamics. This feature is an important future challenge.

6 Code and data availability

The source code of MATCRO will be distributed by request to the corresponding author (Yuji Masutomi: yuji.masutomi@gmail.com). The website for MATCRO-Rice will be developed in the near future.

Appendix A: ρ_a and Q_{sat}

The air density (ρ_a) and the specific humidity at saturation (Q_{sat}) are calculated physically according to the equation for the state of dry air and the Clausius–Clapeyron equation, respectively, as follows:

$$\rho_a = P_a/(R_{dry}T_a), \tag{A1}$$

$$Q_{sat}(T_x, P_a) = (R_{dry}/R_{vap})\{e_{sat}(T_0)\exp\big((\lambda/R_{vap})(1/T_0 - 1/T_x)\big)\}/P_a, \tag{A2}$$

where T_a is air temperature; P_a is air pressure; T_x is temperature of the canopy (T_c) or surface (T_g); T_0 is the melting temperature of the water; R_{dry} and R_{vap} are the gas constants of the dry air and vapour, respectively; $e_{sat}(T_0)$ is the vapour pressure at melting temperature of the water; and λ is the latent heat of vaporization. T_a and P_a are meteorological inputs (Table 1). T_x (T_c or T_g) is calculated in Sect. 3.1. The other parameters are physical constants (Table 5).

Appendix B: Zenith angle θ

According to Goudriaan and van Laar (1994), the zenith angle of the sun (θ) is calculated as follows:

$$\cos(\theta) = \sin(2\pi L_t/360)\sin(\delta_s) + \cos(2\pi L_t/360) \times \cos(\delta_s)\cos(h_{arg}), \tag{B1}$$

$$\delta_s = -\arcsin\big(\sin(23.45(2\pi/360)) \times \cos(2\pi(D_{oy}+10)/365)\big), \tag{B2}$$

$$h_{arg} = 2\pi(h_r - 12)/24, \tag{B3}$$

where L_t is the latitude in radians at the simulation site, δ_s is the declination of the sun, h_{arg} is the hour angle from noon ($h_r = 12$), D_{oy} is the number of days from 1 January at the simulation site, and h_r is the local time at the simulation site.

Appendix C: Coefficients for radiation equations

The coefficients for radiation equations (Eqs. 12–14) are calculated as follows:

$$a_i = F d_f\{(1-t_i)^2 - r_i^2\}^{1/2}, \tag{C1}$$

$$C_{1,i} = \{-(A_{2,i} - r_g)(S_i^d(0) - C_{3,i}D_i^d(0))\exp(-a_i L) + (C_{3,i}r_g + r_g - C_{4,i})D_i^d(0)\exp(-FL\sec(\theta)))\} / A_{3,i}, \tag{C2}$$

$$C_{2,i} = \{(A_{1,i} - r_g)(S_i^d(0) - C_{3,i}D_i^d(0))\exp(a_i L), - (C_{3,i}r_g + r_g - C_{4,i})D_i^d(0)\exp(-FL\sec(\theta))\} / A_{3,i}, \tag{C3}$$

$$C_{3,i} = \sec(\theta)\{t_i\sec(\theta) + d_f t_i(1-t_i) + d_f r_i^2\} / \{d_f^2((1-t_i)^2 - r_i^2) - \sec^2(\theta)\}, \tag{C4}$$

$$C_{4,i} = \{r_i(d_f - \sec(\theta))\sec(\theta))\}/\{d_f^2((1-t_i)^2 - r_i^2) - \sec^2(\theta)\}, \tag{C5}$$

$$A_{1,i} = (1 - t_i + \{(1-t_i)^2 - r_i^2\}^{1/2})/r_i, \tag{C6}$$

$$A_{2,i} = (1 - t_i - \{(1-t_i)^2 - r_i^2\}^{1/2})/r_i, \tag{C7}$$

$$A_{3,i} = (A_{1,i} - r_g)\exp(a_i L) - (A_{2,i} - r_g)\exp(-a_i L), \tag{C8}$$

where i indicates the wavebands of radiation ($i = 1$: PAR; $i = 2$: NIR); r_i and t_i are the leaf reflectivity and transmissivity, respectively; F is the distribution of leaf orientation; d_f is a scattering factor; $A_{3,i}$ is a new variable introduced in Eqs. (C2) and (C3); L is the LAI; r_g is the surface albedo for shortwave radiation; $D_i^d(0)$ and $S_i^d(0)$ are direct and scattered downward radiant flux density at the canopy top, respectively; and θ is the zenith angle of the sun. r_i and t_i are crop-specific parameters determined by Sellers et al. (1996b). F is set to 0.5 from the assumption of random leaf orientation (Goudriaan and van Laar, 1994), and d_f is $\sec(2\pi(53/360))$ (Watanabe and Ohtani, 1995). $A_{3,i}$ is defined in Eq. (C8), L is calculated in the CGM (Eq. 137), and r_g for surface is given in Maruyama and Kuwagata (2010). $D_i^d(0)$ and $S_i^d(0)$ are given in Eqs. (15) and (16), respectively, and θ is calculated in Eq. (B1).

It should be noted that a_i, $A_{1,i}$, and $A_{2,i}$ are not variables determined by constant parameters, while $C_{1,i}$, $C_{2,i}$, $C_{3,i}$, $C_{4,i}$, and $A_{3,i}$ are variables.

Appendix D: Reflectivity and transmissivity of canopies

Reflectivity (r_{ij}) and transmissivity (τ_{ij}) of canopy for each waveband ($i = 1$: PAR, $i = 2$: NIR) and for each direction ($j = 1$: direct, $j = 2$: scattered) are given as follows:

$$r_{i1} = C_{4,i} - C_{3,i}r_{i2}, \tag{D1}$$

$$r_{i2} = (A_{1,i}C_{1,i} + A_{2,i}C_{2,i})/(C_{1,i} + C_{2,i}), \tag{D2}$$

$$\tau_{i1} = (1 + C_{3,i} - C_{4,i}\exp(-FL\sec(\theta))) - C_{3,i}\tau_{i2}, \tag{D3}$$

$$\tau_{i2} = \{(C_{1,i}(1 - A_{1,i})\exp(a_i L)) + C_{2,i}(1 - A_{2,i}\exp(-a_i L))\}/(C_{1,i} + C_{2,i}), \tag{D4}$$

where a_i, $C_{1,i}$, $C_{2,i}$, $C_{3,i}$, $C_{4,i}$, $A_{1,i}$, and $A_{2,i}$, the coefficients of radiation equations (Eqs. 12–14), are calculated as shown in Appendix C, F is a parameter that defines the distribution of leaf orientation, L is the LAI, which is calculated in the CGM (Eq. 137), and θ is the zenith angle of the sun (Appendix B).

Appendix E: d, z_M, z_T, z_Q, z_{Mg}, and z_{Tg}

Zero-plane displacement height (d), roughness lengths of an entire surface for the profiles of momentum, temperature, and specific humidity (z_M, z_T, and z_Q), and roughness lengths that express the effect of surface on the profiles of momentum and temperature ($z_{M\mathrm{g}}$ and $z_{T\mathrm{g}}$) are calculated according to Watanabe (1994) as follows:

$$d = h_{\mathrm{gt}}\left[1 - \frac{1}{A^{+}}\{1-\exp(-A^{+})\}\right], \tag{E1}$$

$$\left(\ln\frac{h_{\mathrm{gt}}-d}{z_M}\right)^{-1} = \left\{1-\exp(-A^{+}) + \left(-\ln\frac{z_{M\mathrm{s}}}{h_{\mathrm{gt}}}\right)^{-1/0.45}\exp(-2A^{+})\right\}^{0.45}, \tag{E2}$$

$$\begin{aligned}\left(\ln\frac{h_{\mathrm{gt}}-d}{z_M}\right)^{-1}\left(\ln\frac{h_{\mathrm{gt}}-d}{z_X}\right)^{-1} = \\ = C_X^{\infty}\left\{1-\exp(-P_{3X}A^{+}) + \left(\frac{C_X^{0}}{C_X^{\infty}}\right)^{1/0.9}\right. \\ \left.\times\exp(-P_{4X}A^{+})\right\}^{0.9},\end{aligned} \tag{E3}$$

$$\left(\ln\frac{h_{\mathrm{gt}}-d}{z_{M\mathrm{g}}}\right)^{2} = \left(\ln\frac{h_{\mathrm{gt}}-d}{z_M}\right)\left(\ln\frac{h_{\mathrm{gt}}-d}{z_M^{+}}\right), \tag{E4}$$

$$\left(\ln\frac{h_{\mathrm{gt}}-d}{z_{M\mathrm{g}}}\right)\left(\ln\frac{h_{\mathrm{gt}}-d}{z_{T\mathrm{g}}}\right) = \left(\ln\frac{h_{\mathrm{gt}}-d}{z_M}\right)\left(\ln\frac{h_{\mathrm{gt}}-d}{z_T^{+}}\right), \tag{E5}$$

$$A^{+} = \frac{c_{\mathrm{m}}L}{2\kappa^{2}}, \tag{E6}$$

$$C_X^{0} = \left(\ln\frac{h_{\mathrm{gt}}-d}{z_M}\right)^{-1}\left(\ln\frac{h_{\mathrm{gt}}-d}{z_X^{+}}\right)^{-1}, \tag{E7}$$

$$C_X^{\infty} = \frac{-1+(1+8F_X)^{0.5}}{2}, \tag{E8}$$

$$F_X = \frac{c_X}{c_{\mathrm{m}}}, \tag{E9}$$

$$\left(\ln\frac{h_{\mathrm{gt}}-d}{z_*^{+}}\right)^{-1} = \frac{1}{-\ln(\frac{z_{*\mathrm{s}}}{h_{\mathrm{gt}}})}\left(\frac{P_{1*}}{P_{1*}+A^{+}\exp(A^{+})}\right)^{P_{2*}}, \tag{E10}$$

$$P_{1*} = 0.00115\left(\frac{z_{*\mathrm{s}}}{h_{\mathrm{gt}}}\right)^{0.1}\exp\left\{5\left(\frac{z_{*\mathrm{s}}}{h_{\mathrm{gt}}}\right)\right\}, \tag{E11}$$

$$P_{2*} = 0.55\exp\left\{-0.58\left(\frac{z_{*\mathrm{s}}}{h_{\mathrm{gt}}}\right)^{0.35}\right\}, \tag{E12}$$

$$P_{3X} = \{F_X + 0.084\exp(-15F_X)\}^{0.15}, \tag{E13}$$

$$P_{4X} = 2F_X^{1.1}, \tag{E14}$$

$$c_{\mathrm{e}} = c_{\mathrm{h}}/(1+c_{\mathrm{h}}(U_{\mathrm{c}}/\overline{g}_{\mathrm{s}})). \tag{E15}$$

Here, $z_{M\mathrm{s}}$, $z_{T\mathrm{s}}$, and $z_{Q\mathrm{s}}$ are the roughness lengths of surface for momentum, temperature, and specific humidity, respectively. In this model, we assume $z_{M\mathrm{s}}$, $z_{T\mathrm{s}}$, and $z_{Q\mathrm{s}} = 0.001$ m (Kimura and Kondo, 1998). c_{m}, c_{h}, and c_{e} are the leaf transfer coefficients for momentum, temperature, and specific humidity, respectively. c_{m} an c_{h} are crop-specific parameters, while c_{e} is calculated in Eq. (E15). h_{gt} and L are crop height and LAI, respectively, and are calculated in the CGM (Eqs. 139 and 137). $\overline{g}_{\mathrm{s}}$ is the stomatal conductance per unit leaf area for both sides of the leaf (Eq. 108). U_{c} is the mean wind speed in the canopy and is calculated in Appendix F. A^{+}, C_X^{0}, C_X^{∞}, z_M^{+}, z_X^{+}, z_*^{+}, P_{1*}, P_{2*}, P_{3X}, P_{4X}, and F_X are the intermediate variables, and κ is the Karman constant. The symbol $*$ indicates M, T, or Q, and the symbol X indicates T or Q.

Appendix F: Mean wind speed in the canopy

Mean wind speed in the canopy (U_{c}) is expressed as

$$U_{\mathrm{c}} = (U_{\mathrm{h}}/\gamma_{\mathrm{m}}h_{\mathrm{gt}}) \times \{1-\exp(-\gamma_{\mathrm{m}}h_{\mathrm{gt}})\}, \tag{F1}$$

$$U_{\mathrm{h}} = U/(1+\ln((z_{\mathrm{a}}-h_{\mathrm{gt}})+1), \tag{F2}$$

$$\gamma_{\mathrm{m}} = c_{\mathrm{m}}(L/h_{\mathrm{gt}})/(2k^{2}), \tag{F3}$$

where U_{h} is the reference wind speed, and γ_{m} is the coefficient of exponential decrease for wind speed in the canopy.

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