Response to Anonymous Referee#1 (gmd-2016-28)

##

In addition to the impact of crop grow, a range of authors have shown that irrigation might have an important impact on the exchange of water and energy between land and atmosphere (it might be useful to add this in your introduction as a justification).

##

You are exactly right. A range of studies have shown the impact of irrigation on the atmosphere.

We added the explanation on the importance of irrigation in land-atmosphere simulations into the introduction of the revised manuscript (P2, L8-L12), referring some studies, e.g., Boucher et al. (2004), Lobell et al. (2006), Snyder et al. (2006), and Kueppers et al. (2008).

##

The paper does not provide an evaluation, a parametrisation and, most important, a validation of the developed model: I know there is a paper part II on this, but I think that the paper cannot stand on its own without these (I suggest the combine part I and II into one paper).

##

The journal guideline of GMD admits the separate submission of the model description and evaluation papers, if the evaluation is extensive. The revised version of the evaluation paper became more extensive, because we added the results of two types of simulations into the revised manuscript of the evaluation paper: the effects of model modifications and the validation of the model at the sites which are independent from the parameterization site. Considering the extent of the model evaluation paper, we think the separate submission is acceptable.

##

It is not always very clear what was already part of MATSIRO and what you have developed.

##

To make clear the difference between the original model and our model, we added Table 3, where all the modifications are listed.

##

It seems to me that only minor adaptations have been implemented up to pg 15 "4.2 Crop development". In this paper you do not describe again all equations of MATSIRO, as this has already been published (you only have to refer to Takata, 2003). By consequence, you can significantly reduce the length of this paper (reduce section 3 to 1-2 pages and section 4.1 to max. 1pg) and add a section on model parametrisation, evaluation and validation.

##

If we only refer to Takata et al. (2003) and do not show the equations, nobody can develop the model and reproduce the results, because Takata et al. (2003) did not describe all parts of MATSIRO. According to the journal guideline of GMD, the model reproducibility is emphasized. Hence, we showed all the equations, which are necessary for developing the model and reproducing the results. We also note that almost of the equations which we showed in the manuscript were not shown in Takata et al. (2003). We think that only referring to Takata et al. (2003) is not a good option for ensuring the model reproducibility.

##

Some small modifications have been described in section 3 and section 4.1. The explicit reasons for these adaptations are not provided. The impacts of these modifications on the model simulations are missing. What are the added values of those adaptations? Do those modifications affect significantly your model simulations (compared to the original LSM set-up)? Are the modifications you implemented specific for rice or are they more generally applicable?

##
We absolutely agree with you. Hence, we showed the effects of the modifications to the revised manuscript of the evaluation paper, by comparing the simulations between the original model and our model.

All the modifications except the consideration of water surface are applicable for other crops. We added this point into the section 2 (P2, L31-32).

##
You assume that your field is flooded (e.g. soil always at saturation level, etc,. . .): is this assumption correct for the whole year round or only valid during the growing season or parts of it? If this assumption is not valid for the whole year round, can you use this model to make climate simulations, as you suggest in your conclusion?
##
The model described in the previous manuscript can’t simulate fluxes for the whole year, because the model focused on only the growing periods of paddy rice. As you pointed out, the model should be able to simulate fluxes for the whole year in order to apply the model to climate simulations. Therefore we improved the model so that it can simulate fluxes for the whole year, even under non-flooded and rainfed condition. To describe the improved model, we drastically modified the model description (throughout the manuscript) and equations (Eqs. 7, 8, 9, 11, 24, 53, 54, 76 and 77) and added new equations (Eqs. 30, 46, 47, 59, 60, 61, 62, 78 and 79). In addition, we validated the simulated LHF and SHF for the whole year in the validation paper.

##
As you do not do an evaluation of your model, you cannot write some of the statements in your abstract (e.g. l2:". . .accurate simulation. . .": you don’t show this in your paper), . . .and conclusion.
##
The statement in the abstract means “accurate simulations in agricultural land are

important for climate simulations”. This is a general statement, but might be misleading. We removed the words “accurate” and “accurately” from the abstract and the introduction. However, we could not find the statements you pointed out in the conclusion. The conclusion just discusses the applicability and limitations of the model.

##

Describe explicitly in your paper which variables (of your adapted model), are now exchanged between the LSM and the GCM, as you mention in introduction at l14.

##

Table 2 shows the variables which are exchanged into the LSM and CGM.

Response to Anonymous Referee#2 (gmd-2016-28)

##

It is my understanding that examples of model output should be provided, with evaluation against standard benchmarks, observations in GMD. There appears to be no reason to divide the model description paper to two papers because both the model description part (this paper) and the validation part (another submitted paper) are not so long. However, if dividing the study into two papers is acceptable, I think this paper is acceptable.

##

Although the present paper does not include the model parameterization and validation, the journal guideline admits the separate submission of model description and evaluation papers, if the evaluation is extensive. The revised version of the evaluation paper became more extensive, because we added the results of two types of simulations into the revised manuscript of the evaluation paper: the effects of model modifications and the validation of the model at the sites which are independent from the parameterization site. Considering the extent of the model evaluation paper, we think the separate submission is acceptable.

##

p. 5, l. 11: Is this assumption appropriate? The model that the authors are developing is rice specific model. However, the leaf orientation of most Poaceae species would not be random. The required preciseness for the leaf orientation may depend on the purpose of the model (or temporal resolution), but the precise description of the leaf orientation may be needed if the purpose of the model is the estimation of hourly fluctuation of the fluxes. If the purpose of the model is the estimation of crop yield for example, the assumption of the leaf orientation may not have critical effect on the estimation. The authors should add the discussion of the appropriateness of the assumption.

##

To be precise, this assumption is not appropriate. The leaf orientation of crops varies with their growing. However, no data is available on the change in the leaf

orientation for rice. Therefore, we assumed that it is random. As you pointed out, the required accuracy depends on the purpose of the model. In the revised manuscript of the evaluation paper, we added the results of the comparison of hourly fluxes between simulations and observations. The results showed that the simulations are in good agreement with the observations for the hourly fluxes.
We added the above discussion into the revised manuscript (P5, L17-19).

##

p. 6, l. 19-20: Please explain in detail.

##

The equation of the scattered factor, df=sec(2pi*(53/360)), is related to the third assumption shown in P5. The detail of the assumption was explained at P5 L19-20 in the revised manuscript. To make clear the relation between the equation and assumption, we modified the sentence (P6, L25).

##

p. 11, l. 28: The down-regulation effect of photosynthesis has a very profound effect on crop growth. The parameters relevant to photosynthesis down-regulation in Arora et al. (2009) are calculated using mainly plants other than rice. Therefore, the authors should explain the applicability of the parameter values to rice.

##

We think the down-regulation effect is limited under the current CO2 concentration, but significant under the future. In the manuscript, we “tentatively” used the mean value for the key parameter in the equation of down-regulation in Arora et al. (2009), because there is no information on the key parameter of the equation for rice, according to our knowledge, and the CO2 effect on crop growth still has a large uncertainty. If the value for the key parameter is quantified in the future, the tentative value should be replaced. We added the above discussion into the revised manuscript (P13, L3 - P13, L7).

##

Eq. 69-71: Please change the variable name of "Qt". The The character "Q" is already used for the photon flux density.

##

We changed the symbol to “q” in the revised manuscript (P14, Eq. 80).

##

All equations: Italic should be used for only scalars in principle. For example, it may be preferable not to use Italic for the subscript “c” of “Hc” if “c” is not scalar value. Moreover, upright font (not italic) should be used for multi-letter variables (for example, “Rnc”). Please recheck almost of all subscripts and superscripts of the equations.

##

According to your comments, we modified the symbols for all the variables and parameters (throughout the manuscript).

A land surface model combined with a crop growth model for paddy rice (MATCRO-Rice Ver. 1) – Part I: 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, ~~accurate~~ 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 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 ~~flux~~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 to 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 ~~accurately~~ simulate the fluxes of heat, water, and gases in agricultural land.

A 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 ~~flux~~ 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 ~~a flooded~~ 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 ~~surface.~~ and rainfed 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 ~~flux~~uptake by crop, and crop yields by exchanging variables between the LSM and CGM. Herein, we first provide the overview of MATCRO-Rice in Section 2, and then describe the LSM and CGM of MATCRO-Rice in detail in Sections 3 and 4, respectively. Last, we discuss the applications and limitations of MATCRO-Rice in Section 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.

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~~water~~", "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 ~~to represent a flooded surfacein paddy rice fields~~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 (Section 4).

3.1 Energy balance at the canopy and surface~~water~~

This module calculates LHF and SHF by solving energy balance at two layers~~above the soil~~, canopy and surface~~water~~. 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 ~~water~~ are given as follows:

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

$$R_{nw\mathrm{ng}} = H_{w\mathrm{g}} + \lambda E_{w\mathrm{g}} + G_{ws\mathrm{gs}} + S_{tw\mathrm{tw}}, \qquad \text{(Water surface)(Surface)} \qquad (2)$$

where ~~R_{nc} and R_{nw}~~ R_{nc} and R_{ng} are the net radiant flux density at canopy and surface~~water, H_c and H_w~~ , H_{c} and H_{g} are the SHF from the canopy and surface~~water, E_c, E_t, and E_w~~ , E_{c}, E_{t}, and E_{g} are the evaporation from wet canopy, transpiration from the canopy, and evaporation from the surface~~water~~, respectively, ~~G_{ws}~~ G_{gs} is the heat flux from the surface ~~water~~ to soil, and ~~S_{tw}~~ S_{tw} is the heat flux stored into surface water in the case of flooded surface. It is important to note that the downward flux for ~~R_{nc}, R_{nw}, and G_{ws}~~ R_{nc}, R_{ng}, and G_{gs} indicates a positive flux, whereas downward flux for ~~H_c, H_w, E_c, E_t, and E_w~~ 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 vaporisation (Table 5). Each radiant, heat, and water flux in Eqs. 1 and 2 are given by the following equations.

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

$$R_{nw\mathrm{ng}} = (R^{d}_{s}(0)^{\mathrm{d}}_{\mathrm{s}}(0) - R^{u}_{s}(0)^{\mathrm{u}}_{\mathrm{s}}(0))\tau_{cs\mathrm{cs}} + \epsilon R^{d}_{l}(0)^{\mathrm{d}}_{\mathrm{l}}(0)\tau_{cl\mathrm{cl}} - \epsilon\sigma T^{4}{}_{w\mathrm{g}} + \epsilon\sigma(1-\tau_{cl\mathrm{cl}})T^{4}{}_{c\mathrm{c}}, \tag{4}$$

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

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

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

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

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

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

$$S_{tw\mathrm{tw}} = c_{pw}\rho_w d_w(dT_w/dt), \begin{cases} c_{\mathrm{pw}}\rho_{\mathrm{w}} d_{\mathrm{w}}(dT_{\mathrm{g}}/dt), & (\text{flooded}), \\ 0 & (\text{unflooded}) \end{cases} \tag{11}$$

where ~~$R^d_s(0)$, $R^d_l(0)$, and $R^u_s(0)$~~ $R^{\mathrm{d}}_{\mathrm{s}}(0)$, $R^{\mathrm{d}}_{\mathrm{l}}(0)$, and $R^{\mathrm{u}}_{\mathrm{s}}(0)$ 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}~~ τ_{cs} and τ_{cl} are the canopy transmissivity for shortwave and longwave radiation, respectively, ~~C_{Hc} and C_{Hw}~~ C_{Hc} and C_{Hg} are the bulk transfer coefficients (BTCs) for sensible heat between canopy and atmosphere and between surface ~~water~~ and atmosphere, respectively, ~~C_{Ec} and C_{Ew}~~ C_{Ec} and C_{Eg} are the BTCs for latent heat between canopy and atmosphere and between ~~canopy~~ surface and atmosphere, respectively, ~~T_a, P_a~~ T_{a}, P_{a}, U, and Q are air temperature, air pressure, wind speed, and specific humidity, respectively, ~~f_{cw}~~ f_{cw} is the fraction of wet canopy, ~~T_c, T_w, and $T_s(0)$~~ h_{ms} is humidity of the topsoil, T_{c}, T_{g}, and $T_{\mathrm{s}}(0)$ are the canopy, surface~~water, and soil surface~~ , and topsoil temperature, respectively, ~~c_{pa} and c_{pw} are the~~ $E_{\mathrm{t,max}}$, $E_{\mathrm{g,max}}$, and $E_{\mathrm{c,max}}$ 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~~ k_{w} is the water thermal conductivity, ~~ρ_w and ρ_a~~ ρ_{w} and ρ_{a} are water and air density, respectively, σ is the Boltzmann constant, ~~Q_{sat}~~ Q_{sat} is specific humidity at saturation, ~~d_w~~ d_{w} is the depth of surface water in the case of flooded surface, ϵ is the longwave emissivity of surface~~water~~, 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, ~~$R^d_s(0)$, $R^d_l(0)$, and $R^u_s(0)$~~ $R^{\mathrm{d}}_{\mathrm{s}}(0)$, $R^{\mathrm{d}}_{\mathrm{l}}(0)$, and $R^{\mathrm{u}}_{\mathrm{s}}(0)$ indicate the radiant flux density at the canopy top, and ~~$T_s(0)$~~ $T_{\mathrm{s}}(0)$ indicates the soil surface temperature.

~~T_a, P_a~~ T_{a}, P_{a}, U, Q, ~~$R^d_s(0)$, and $R^d_l(0)$~~ $R^{\mathrm{d}}_{\mathrm{s}}(0)$, and $R^{\mathrm{d}}_{\mathrm{l}}(0)$ are meteorological forcing inputs (Table 1). ~~$R^u_s(0)$, τ_{cs}, τ_{cl}, f_{cw}, C_{Ec}, C_{Ew}, C_{Hc}, C_{Hw}, and $T_s(0)$~~ $R^{\mathrm{u}}_{\mathrm{s}}(0)$, τ_{cs}, τ_{cl}, f_{cw}, h_{ms}, C_{Ec}, C_{Eg}, C_{Hc}, C_{Hg}, $T_{\mathrm{s}}(0)$, $E_{\mathrm{t,max}}$, $E_{\mathrm{g,max}}$ and $E_{\mathrm{c,max}}$ are calculated from Eqs. 21, 20, 23, 40, 60, 25, 24, 27, 26, ~~and 48,~~ 48, 61, 62 and 47, respectively, which are given in the following sections. The variables ~~ρ_a and Q_{sat}~~ 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~~ c_pa, c_pw, k_w, ρ_w, and σ are physical constants (Table 5), ~~d_w~~ d_w is a simulation setting parameter (Table 6), and ϵ is set to 0.96 (Campbell and Norman, 1998). ~~T_c and T_w~~ T_c and T_g are numerically determined to satisfy Eqs. 1 to 11. The numerical method is described in Masutomi et al. (2016).

~~The original MATSIRO uses C_{Hc} instead of C_{Ec} in Eq. 8 when specific humidity of the air is greater than the saturated specific humidity of the canopy (i.e., $Q_{sat} - Q < 0$), because dew condensation occurs at canopy of interest. MATCRO does not consider the effect for simplicity. It should be noted that C_{Hc} is used for calculating the evaporation from wet canopy in Eq. 7.~~ Irrigation and flooded surface start at $D_\mathrm{oy,Is}$ and end at $D_\mathrm{oy,Ie}$. $D_\mathrm{oy,Ie}$ and $D_\mathrm{oy,Ie}$ 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 (Section 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 (Section 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]). 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 income from a zenith angle of 53°.

~~It should be noted that the~~ The first assumption may affect the accuracy of the model simulations. We know that leaf orientation of crops varies with their growth. However, there is no data on the change in leaf orientation for rice. Therefore, we assumed that the leaf orientation is random during the growing period. The 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 (~~$D^d_i(l)$~~ $D^\mathrm{d}_i(l)$), downward scattered (~~$S^d_i(l)$~~ $S^\mathrm{d}_i(l)$), and upward scattered (~~$S^u_i(l)$~~ $S^\mathrm{u}_i(l)$) within canopy for each waveband ($i = 1$: PAR; $i = 2$: NIR), as follows:

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

$$S^{d}_{\_}{}^{\mathrm{d}}{}_i(l) = C_{1,i}\exp(a_il) + C_{2,i}\exp(-a_il) + C_{3,i}D^{d}_{\_}{}^{\mathrm{d}}{}_i(l), \tag{13}$$

$$S^{u}_{\_}{}^{\mathrm{u}}{}_i(l) = A_{1,i}C_{1,i}\exp(a_il) + A_{2,i}C_{2,i}\exp(-a_il) + C_{4,i}D^{d}_{\_}{}^{\mathrm{d}}{}_i(l). \tag{14}$$

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()~~ 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. ~~$D^d_i(0)$~~ $D^{\mathrm{d}}_i(0)$ is obtained by splitting radiant flux density for downward shortwave at the top of the canopy into direct and scattered radiation as follows:

$$D^{d\mathrm{d}}{}_i(0) = 0.5R^d_s(0)^{\mathrm{d}}_{\mathrm{s}}(0)(1-f_{df\,\mathrm{df}}), \tag{15}$$

$$S^{d\mathrm{d}}{}_i(0) = 0.5R^d_s(0)^{\mathrm{d}}_{\mathrm{s}}(0)f_{df\,\mathrm{df}}, \tag{16}$$

where ~~$R^d_s(0)$~~ $R^{\mathrm{d}}_{\mathrm{s}}(0)$ is the downward shortwave radiant flux density at the canopy top and ~~f_{df}~~ 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 ~~$R^d_s(0)$~~$R^{\mathrm{d}}_{\mathrm{s}}(0)$. According to Goudriaan and van Laar (1994), ~~f_{df}~~ f_{df} is given as a function of the transmissivity of atmosphere (~~τ_{atm}~~τ_{atm}) as follows:

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

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

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

where ~~R_{ex}~~ R_{ex} is the extraterrestrial radiation, ~~R_{sun}~~ R_{sun} is the solar constant, and ~~D_{oy}~~ D_{oy} is the number of days from Jan 1. The equations 15–19 that calculate ~~$D^d_i(0)$~~ $D^{\mathrm{d}}_i(0)$ 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}~~τ_{cs}) is expressed as

$$\tau_{cs\,\mathrm{cs}} = R^{d\mathrm{d}}_{s\mathrm{s}}(L)/(R^d_s(0)^{\mathrm{d}}_{\mathrm{s}}(0) - R^u_s(0)^{\mathrm{u}}_{\mathrm{s}}(0)). \tag{20}$$

Here, ~~$R^u_s(0)$ and $R^d_s(L)$~~ $R^{\mathrm{u}}_{\mathrm{s}}(0)$ and $R^{\mathrm{d}}_{\mathrm{s}}(L)$ 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 (Section 4.4). ~~$R^u_s(0)$ and $R^d_s(L)$~~ $R^{\mathrm{u}}_{\mathrm{s}}(0)$ and $R^{\mathrm{d}}_{\mathrm{s}}(L)$ are represented by

$$R^u_s(0)^{\mathrm{u}}_{\mathrm{s}}(0) = r_{11}D^{d\mathrm{d}}{}_1(0) + r_{21}D^{d\mathrm{d}}{}_2(0) + r_{12}S^{d\mathrm{d}}{}_1(0) + r_{22}S^{d\mathrm{d}}{}_2(0), \tag{21}$$

$$R^{d\mathrm{d}}_{s\mathrm{s}}(L) = \tau_{11}D^{d\mathrm{d}}{}_1(0) + \tau_{21}D^{d\mathrm{d}}{}_2(0) + \tau_{12}S^{d\mathrm{d}}{}_1(0) + \tau_{22}S^{d\mathrm{d}}{}_2(0), \tag{22}$$

where r_{ij} and τ_{ij} are the canopy reflectivity and transmissivity, respectively, 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}~~τ_{cl}) is expressed as

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

where, ~~d_f~~ d_{f} is the scattered factor. We set ~~$d_f = \sec(2\pi(53/360))$ from the assumption that scattered radiation income is from a zenith angle of 53° (Watanabe, 1994)~~$d_{\mathrm{f}} = \sec(2\pi(53/360))$ 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_{Ec}, C_{Ew}, C_{Hc}, and C_{Hw}~~C_{Ec}, C_{Eg}, C_{Hc}, and C_{Hg}). The BTCs are used to simulate energy balance (Section 3.1). This module is based on Watanabe (1994), where ~~C_{Ew}, C_{Ec}, C_{Hw}, and C_{Hc}~~ C_{Eg}, C_{Ec}, C_{Hg}, and C_{Hc} are given by

$$C_{Ew\mathrm{Eg}} = \kappa^2 \left[\ln\left(\frac{z_a-d}{z_{Mw}}\right) 1/C_{\mathrm{Hg}} + \Psi_M(\zeta_w) r_{\mathrm{s}} U\right]^{-1} \ln\left(\frac{z_a-d}{z_{Qw}}\right) + \Psi_E(\zeta_w)^{-1}, \tag{24}$$

$$C_{Ec\mathrm{Ec}} = C_{E\mathrm{E}} - C_{Ew\mathrm{Eg}}, \tag{25}$$

$$C_{Hw\mathrm{Hg}} = \kappa^2 \left[\ln\left(\frac{z_a-d}{z_{Mw}}\right) \ln\left(\frac{z_{\mathrm{a}}-d}{z_{\mathrm{Mg}}}\right) + \Psi_{M\mathrm{M}}(\zeta_{w\mathrm{g}})\right]^{-1} \left[\ln\left(\frac{z_a-d}{z_{Tw}}\right) \ln\left(\frac{z_{\mathrm{a}}-d}{z_{\mathrm{Tg}}}\right) + \Psi_{H\mathrm{H}}(\zeta_{w\mathrm{g}})\right]^{-1}, \tag{26}$$

$$C_{Hc\mathrm{Hc}} = C_{H\mathrm{H}} - C_{Hw\mathrm{Hg}}, \tag{27}$$

where ~~C_E and C_H~~ C_{E} and C_{H} are the BTCs for latent and sensible heat between the entire surface (canopy + surface~~water~~) and atmosphere and are given by

$$C_{E\mathrm{E}} = \kappa^2 \left[\ln\left(\frac{z_a-d}{z_M}\right) \ln\left(\frac{z_{\mathrm{a}}-d}{z_{\mathrm{M}}}\right) + \Psi_{M\mathrm{M}}(\zeta)\right]^{-1} \left[\ln\left(\frac{z_a-d}{z_Q}\right) \ln\left(\frac{z_{\mathrm{a}}-d}{z_{\mathrm{Q}}}\right) + \Psi_{E\mathrm{E}}(\zeta)\right]^{-1}, \tag{28}$$

$$C_{H\mathrm{H}} = \kappa^2 \left[\ln\left(\frac{z_a-d}{z_M}\right) \ln\left(\frac{z_{\mathrm{a}}-d}{z_{\mathrm{M}}}\right) + \Psi_{M\mathrm{M}}(\zeta)\right]^{-1} \left[\ln\left(\frac{z_a-d}{z_T}\right) \ln\left(\frac{z_{\mathrm{a}}-d}{z_{\mathrm{T}}}\right) + \Psi_{H\mathrm{H}}(\zeta)\right]^{-1}. \tag{29}$$

In Eqs. 24 to ~~??~~29, κ is the Karman constant, d is the zero-plane displacement height, ~~z_a~~ z_{a} is the reference height at which wind velocity is observed, ~~z_{Mw}, z_{Tw}, z_{Qw}~~ z_{Mg} and z_{Tg} are the roughness lengths that express the effect of surface ~~water~~ on the profiles of momentum ~~, temperature, and specific humidity, respectively, z_M, z_T, and z_Q~~ and temperature, respectively, z_{M}, z_{T}, and z_{Q} are the roughness lengths of an entire surface (canopy + surface~~water~~) for the profiles of momentum, temperature, and specific humidity, respectively~~. z_a~~ , 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_{Mw}, z_{Tw}, and z_{Qw}~~ z_{M}, z_{T}, z_{Q}, z_{Mg} and z_{Tg} are the functions of crop height and LAI (Appendix E). ~~Ψ_M, Ψ_H,~~ r_{s} is given by

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

where $w_{\mathrm{s}}(0)$ is the water content of topsoil and is calculated in Eq. 53, and ~~Ψ_E~~ 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:

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

$$\Psi_{H\mathrm{H}}(\zeta) = \Psi_{E\mathrm{E}}(\zeta) = \begin{cases} 6\ln(1+\zeta) & (\zeta > 0:\text{stable}) \\ -2\ln\left[\frac{1+(1-16\zeta)^{1/2}}{2}\right] & (\text{Otherwise: stable}). \end{cases} \tag{32}$$

The equations above are adopted from Campbell and Norman (1998), whereas the original MATSRIO 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 ~~water~~ and atmosphere (~~ζ_w~~ζ_{g}). These are given by

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

$$\zeta_{w\mathrm{g}} = \frac{z_a-d}{L_{MOw}}\frac{z_{\mathrm{a}}-d}{L_{\mathrm{MOg}}}, \tag{34}$$

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

$$L_{MO\mathrm{MO}} = \frac{\Theta_0 C_M^{3/2} U^2}{\kappa g\{C_{Hw}(T_w-T_a)+C_{Hc}(T_c-T_a)\}}\frac{\Theta_0 C_{\mathrm{M}}^{3/2} U^2}{\kappa g\{C_{\mathrm{Hg}}(T_{\mathrm{g}}-T_{\mathrm{a}})+C_{\mathrm{Hc}}(T_{\mathrm{c}}-T_{\mathrm{a}})\}}, \tag{35}$$

$$L_{MOw\mathrm{MOg}} = \frac{\Theta_0 C_{Mw}^{3/2} U^2}{\kappa g C_{Hw}(T_w-T_a)}\frac{\Theta_0 C_{\mathrm{Mg}}^{3/2} U^2}{\kappa g C_{\mathrm{Hg}}(T_{\mathrm{g}}-T_{\mathrm{a}})}, \tag{36}$$

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

$$\Theta_0 = T_{a\mathrm{a}} * (1.0*10^5/P_{a\mathrm{a}})^{(R_{dry}/c_{pa})(R_{\mathrm{dry}}/c_{\mathrm{pa}})}, \tag{37}$$

where ~~R_{dry}~~ 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_{Mw}~~ C_{M} and C_{Mg} are given by

$$C_{M\mathrm{M}} = k^2\left[\ln\left(\frac{z_a-d}{z_M}\right)\ln\left(\frac{z_{\mathrm{a}}-d}{z_{\mathrm{M}}}\right)+\Psi_{M\mathrm{M}}(\zeta)\right]^{-2}, \tag{38}$$

$$C_{Mw\mathrm{Mg}} = k^2\left[\ln\left(\frac{z_a-d}{z_{Mw}}\right)\ln\left(\frac{z_{\mathrm{a}}-d}{z_{\mathrm{Mg}}}\right)+\Psi_{M\mathrm{M}}(\zeta_{w\mathrm{g}})\right]^{-2}. \tag{39}$$

Now we have six independent equations, Eqs. 24, 25, 26, 27, 38, and 39, for six unknown variables, ~~C_{Ew}, C_{Ec}, C_{Hw}, C_{Hc}, C_M, and C_{Mw}~~ C_{Eg}, C_{Ec}, C_{Hg}, C_{Hc}, C_{M}, and C_{Mg}, respectively. Therefore, we can determine the values of these variables by numerically solving Eqs. 24 to 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}~~ f_{cw}) which is used for simulating energy balance at canopy (Section 3.1). To calculate ~~f_{cw}~~ 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}~~ f_{cw} is given as

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

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

$$\rho_{w}\frac{dw_c}{dt}{}_{\mathrm{w}}\frac{dw_{\mathrm{c}}}{dt} \;=\; I_{c\mathrm{c}} - D_{g\mathrm{g}} - E_{c\mathrm{c}}, \tag{41}$$

where ~~ρ_w~~ ρ_{w} is the density of water, ~~I_c~~ I_{c} is the amount of precipitation intercepted by canopy, ~~D_g~~ D_{g} is the amount of water that falls from the canopy onto surface ~~water~~ due to gravity, and ~~E_c~~ E_{c} is the amount of water that evaporates from the canopy (Eq. 7). ~~I_c~~ I_{c} depends on the amount of precipitation (~~P_r~~ P_{r}) and LAI (L) and is given by

$$I_{c\mathrm{c}} \;=\; f_{int\mathrm{int}} P_{r\mathrm{r}}, \tag{42}$$

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

where ~~f_{int}~~ 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}~~ D_{g} and w_{cap} are given as

$$D_{g\mathrm{g}} \;=\; \rho_{w\mathrm{w}} D_1 \exp(D_2 w_{c\mathrm{c}}), \tag{44}$$

$$w_{cap\mathrm{cap}} \;=\; (W_{sh\mathrm{sh}} * 10^{-4})/\rho_{w\mathrm{w}}, \tag{45}$$

respectively, where D_1 and D_2 are parameters (Rutter et al., 1975), and ~~W_{sh}~~ 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

$$F_{\mathrm{c}} \;=\; D_{\mathrm{g}} + (1 - f_{\mathrm{int}})P_{\mathrm{r}} + \max\{0, w_{\mathrm{c}} - w_{\mathrm{cap}}\}\rho_{\mathrm{w}}/\delta t, \quad \text{(unflooded)} \tag{46}$$

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 ($E_{\mathrm{c,max}}$) is given by

$$E_{\mathrm{c,max}} \;=\; w_{\mathrm{c}}\rho_{\mathrm{w}}/\delta t. \tag{47}$$

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 (~~$T_s(0)$~~$T_\mathrm{s}(0)$), which is used for simulating energy balance of the surface ~~water~~ (Section 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 (~~$T_s(z)$~~$T_\mathrm{s}(z)$) is calculated from the gradient of heat flux in the soil as follows:

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

where ~~c_{hs}~~ c_hs is the volumetric heat capacity of the soil and ~~$G_s(z)$~~ $G_\mathrm{s}(z)$ is the heat flux at a soil depth of z and is given from the gradient of soil temperature

$$G_{s\,\mathrm{s}}(z) = \begin{cases} k_\mathrm{ts}(z)\frac{\partial T_\mathrm{s}(z)}{\partial z} & (0 \le z < z_\mathrm{max}) \\ 0 & (z = z_\mathrm{max}). \end{cases} \tag{49}$$

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

$$c_{hs\,\mathrm{hs}}(z) = \rho_{s\,\mathrm{s}} c_{pm\,\mathrm{pm}} + \rho_{w\,\mathrm{w}} c_{pw\,\mathrm{pw}} w_{s\,\mathrm{s}}(z), \tag{50}$$

where ~~ρ_s~~ ρ_s is the bulk density of soil, ~~c_{pm}~~ c_pm is the specific heat of soil minerals, and ~~$w_s(z)$~~ $w_\mathrm{s}(z)$ is the volumetric concentration of soil water. ~~ρ_s~~ ρ_s is a soil-type specific parameter determined by soil type at a simulation site, and ~~c_{pm}~~ 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 MATSRIO 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}~~ c_hs is not considered in MATCRO. The parameter ~~$k_{ts}(z)$~~ $k_\mathrm{ts}(z)$ in Eq. 49 is given by

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

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

where ~~k_{ts0} and k_{tss}~~ k_ts0 and k_tss are the thermal conductivity of dry and saturated soils, respectively, ~~K_e~~ K_e is the Kersten number, and ~~w_{sat}~~ w_sat is the volumetric soil water concentration at saturation. ~~k_{ts0} and k_{tss}~~ k_ts0 and k_tss are parameters. We set ~~k_{ts0}~~k_ts0=0.25 (Campbell and Norman, 1998), and ~~k_{tss}~~ k_tss = 1.58 (Best et al., 2011). The parameter ~~w_{sat}~~ w_sat is specific to soil type. Equations 51 and 52 for the calculation of ~~$k_{ts}(z)$~~ $k_{\mathrm{ts}}(z)$ are based on the equations developed by Best et al. (2011), while the original MATSIRO employs a different equation. The variable ~~$w_s(z)$~~ $w_{\mathrm{s}}(z)$ depends on the gradient of water flux and absorption by roots at a soil depth z~~and is given by~~. In addition, water flux from the canopy layer is added into the top layer of the soil ($0 \le z < z_{\mathrm{t}}$) in the case of non-flooded surface. The variable $w_{\mathrm{s}}(z)$ is given by

$$w_s(z)\frac{\partial w_{\mathrm{s}}(z)}{\partial t} = w_{sat} \qquad (0 z z_{sat}), \frac{\partial w_s(z)}{\partial t} = \frac{\partial F_s(z)}{\partial z} + S_s(z) \qquad (z_{sat} < z z_{max}), \begin{cases} \frac{\partial F_{\mathrm{s}}(z)}{\partial z} - S_{\mathrm{s}}(z) + F_{\mathrm{c}} & (0 \le z < z_{\mathrm{t}}), \\ \frac{\partial F_{\mathrm{s}}(z)}{\partial z} - S_{\mathrm{s}}(z) & (z_{\mathrm{t}} < z \le z_{\mathrm{b}}), \end{cases} \tag{53}$$

where ~~$F_s(z)$ and $S_s(z)$~~ $F_{\mathrm{s}}(z)$ and $S_{\mathrm{s}}(z)$ are water flux and absorption by roots at a soil depth of z, respectively. ~~For simplicity, the top soil~~ 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 ~~, because the surface above soil is flooded. Given the assumption, we do not need to explicitly simulate water flow from a flooded surface into soil.~~ as follows,

$$w_{\mathrm{s}}(z) = w_{\mathrm{sat}} \qquad (\text{if flooded}; 0 \le z < z_{\mathrm{t}}). \tag{54}$$

This assumption is not considered in the original MATSIRO. ~~z_{sat}~~ z_{t} is a simulation setting parameter. ~~$F_s(z)$~~ $F_{\mathrm{s}}(z)$ is calculated from the gradient of water potentials as follows.

$$F_{s\mathrm{s}}(z) = \begin{cases} -K(z)\left(\frac{\partial \psi(z)}{\partial z} + 1\right) & (0 \le z \le z_{\mathrm{b}}) \\ (w_{\mathrm{sat}}/\tau_{\mathrm{b}})(w_{\mathrm{s}}(z)/w_{\mathrm{sat}})^2 & (z_{\mathrm{b}} < z \le z_{\mathrm{max}}) \end{cases}, \tag{55}$$

where $K(z)$ is the hydraulic conductivity and $\psi(z)$ is the water potential at a soil depth of z. ~~$F_s(z)$~~ $F_{\mathrm{s}}(z)$ in the bottommost layer (~~$z_b < z < z_{max}$~~$z_{\mathrm{b}} < z < z_{\mathrm{max}}$) represents the base flow, and ~~τ_b~~ 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~~ z_{b} is a simulation setting parameter, and ~~τ_b~~ 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.

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

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

where ~~K_s and ψ_s~~ 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~~K_{s}, ψ_{s}, and B are soil-type specific parameters. ~~$S_s(z)$~~ $S_{\mathrm{s}}(z)$ in Eq. ~~??~~ 53 is calculated from the transpiration

$$S_{s\mathrm{s}}(z) = \begin{cases} (E_{\mathrm{t}}/\rho_{\mathrm{w}})f_{\mathrm{r}}(z) & (0 \le z \le z_{\mathrm{rt}}) \\ 0 & (z_{\mathrm{rt}} < z \le z_{\mathrm{max}}) \end{cases}, \tag{58}$$

where ~~E_T~~ E_t is the transpiration calculated in Eq. 8~~and z_{rt}~~ , z_rt is a root depth calculated by the CGM (Eq. 140)~~. In Eq. 58,~~ , $f_\mathrm{r}(z)$ is the distribution of 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 ~~$S_s(z)$ has no dependency on soildepth~~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 crop can use soil water beyond the wilting point with water potential of -1500kPa (w_wlt). Hence the maximum transpiration ($E_\mathrm{t,max}$) is given by

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

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

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

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~~ A_n) in canopy for simulating crop growth. In addition, the stomatal conductance per unit leaf area for both sides of the leave (~~g_s~~ g_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~~ A_n per unit leaf area for each the sunlit and shade leaves are calculated. The second refinement is that ~~A_n~~ A_n for the entire canopy is calculated considering vertical distribution of nitrogen within the canopy.

~~A_n~~ A_n for the entire canopy is given by

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

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

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

where ~~$\overline{A}_{g,x}$ and $\overline{R}_{d,x}$~~ $\overline{A}_{\mathrm{g},x}$ 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}~~ sn or sh. L_sn and L_sh are given as follows.

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

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

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

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

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 CO$_2$ is represented as follows:

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

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

where ~~$\overline{A}_{g',x}$~~ $\overline{A}_{\mathrm{g}',x}$ is gross carbon assimilation per unit leaf area for sunlit and shade leaves without photosynthesis down-regulation, ~~f_{dwn}~~ f_dwn is the factor for photosynthesis down-regulation, ~~γ_{gd} and γ_g~~ γ_gd and γ_g are parameters that characterize the response to increased CO$_2$, $C_\mathrm{a,ppm}$ is atmospheric CO$_2$ concentration, and C_0 is the base concentration of 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 ~~$\gamma_{gd} = 0.42$, $\gamma_g = 0.9$~~$\gamma_\mathrm{gd} = 0.42$, $\gamma_\mathrm{g} = 0.9$, 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 ~~$\overline{A}_{g',x}$ and $\overline{R}_{d,x}$~~ $\overline{A}_{\mathrm{g}',x}$ and $\overline{R}_{\mathrm{d},x}$ is based on the leaf photosynthesis model developed by Collatz et al. (1991). In their model, ~~$\overline{A}_{g',x}$~~ $\overline{A}_{\mathrm{g}',x}$ is determined by three limiting factors: Rubisco, light, and sucrose synthesis, as follows:

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

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

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

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

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

$$\overline{\omega}_{\underline{c,x}\mathrm{c},x} = \overline{V}_{\underline{mc,x}\mathrm{mc},x}\left\{\underline{\frac{c_{i,x}-\Gamma^*}{c_{i,x}+K_c(1+[\mathrm{O}_2]/K_O)}}\frac{c_{\mathrm{i},x}-\Gamma^*}{c_{\mathrm{i},x}+K_\mathrm{c}(1+[\mathrm{O}_2]/K_\mathrm{O})}\right\} \tag{73}$$

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

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

Here, ~~$\overline{V}_{mc,x}$ and $\overline{V}_{ms,x}$~~ $\overline{V}_{\mathrm{mc},x}$ and $\overline{V}_{\mathrm{ms},x}$ are the maximum Rubisco capacity per unit leaf area for ~~$\overline{\omega}_{c,x}$ and $\overline{\omega}_{s,x}$~~ $\overline{\omega}_{\mathrm{c},x}$ and $\overline{\omega}_{\mathrm{s},x}$, respectively, ~~$c_{i,x}$~~ $c_{\mathrm{i},x}$ is the partial pressure of intercellular CO_2, $[O_2]$ is the partial pressure of intercellular O_2, ~~$\overline{Q}_x$~~ $\overline{Q}_x$ is the photon flux density for PAR absorbed per unit leaf area by sunlit and shade leaves, ~~ϵ_e~~ ϵ_e is the quantum efficiency, Γ^* is the light compensation point, and ~~K_c and K_O~~ 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~~ ϵ_e is a crop specific parameter. ~~$\overline{V}_{mc,x}$ and $\overline{V}_{ms,x}$~~ $\overline{V}_{\mathrm{mc},x}$ and $\overline{V}_{\mathrm{ms},x}$ are given by

$$\overline{V}_{\underline{mc,x}\mathrm{mc},x} = \overline{V}_{\underline{max,x}}\underline{2^{Q_t}/\{1+\exp(s_1(T_c-s_2))\}}_{\mathrm{max},x}f_\mathrm{v}[2^{q_\mathrm{t}}/\{1+\exp(s_1(T_\mathrm{c}-s_2))\}], \tag{76}$$

$$\overline{V}_{\underline{ms,x}\mathrm{ms},x} = \overline{V}_{\underline{max,x}}\underline{2^{Q_t}/\{1+\exp(s_3(s_4-T_c))\}}_{\mathrm{max},x}f_\mathrm{v}[2^{q_\mathrm{t}}/\{1+\exp(s_3(s_4-T_\mathrm{c}))\}], \tag{77}$$

where ~~$\overline{V}_{max,x}$~~ $\overline{V}_{\mathrm{max},x}$ is the reference value for the maximum Rubisco capacity per unit leaf area of sunlit (~~$\overline{V}_{max,sn}$~~ $\overline{V}_{\mathrm{max,sn}}$) and shade (~~$\overline{V}_{max,sh}$~~ $\overline{V}_{\mathrm{max,sh}}$) 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 $\overline{V}_{ms,x}$~~ $\overline{V}_{\mathrm{max},x}$ on $\overline{V}_{\mathrm{mc},x}$ or $\overline{V}_{\mathrm{ms},x}$, q_t is a function that represents temperature dependency. The variables s_1 and s_2 are parameterised 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. ~~Q_t~~ f_v is given by

$$\underline{Q_t}f_\mathrm{v} = \int_0^{r_\mathrm{t}} f_\mathrm{r}(\underline{T_c-298}z)\underline{/10.}f_\mathrm{s}(z)dz, \tag{78}$$

$$f_\mathrm{s}(z) = \frac{2}{1+\exp(-\gamma_\mathrm{s}\psi_\mathrm{s}(z))}, \tag{79}$$

~~$\overline{V}_{max,sn}$ and $\overline{V}_{max,sh}$~~ 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. Eq. 79 is based on Bouman et al. (2001), although the original MATSIRO uses a different equation. q_t is given by

$$q_\mathrm{t} = (T_\mathrm{c} - 298)/10. \tag{80}$$

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

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

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

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

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

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

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

$$K_{c\mathrm{c}} = 30 \times 2.1^{Q_t q_\mathrm{t}}, \tag{85}$$

$$K_{O\mathrm{O}} = 30000 \times 1.2^{Q_t q_\mathrm{t}}, \tag{86}$$

$$S = 2600 \times 0.57^{Q_t q_\mathrm{t}}, \tag{87}$$

where S is the ratio of the partition of RuBP to the caboxylase 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}~~ Q_sn) and shade (~~Q_{sh}~~ Q_sh) leaves. ~~Q_{sn} and Q_{sh}~~ Q_sn and Q_sh consist of direct and scattered components and are given as

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

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

where ~~$Q_{sn,d}$, $Q_{sn,s}$, and $Q_{sh,s}$~~ $Q_{\mathrm{sn,d}}$, $Q_{\mathrm{sn,s}}$, and $Q_{\mathrm{sh,s}}$ 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

$$Q_{\underline{sn,d}\mathrm{sn,d}} = k_{\underline{q}\mathrm{q}}\int_0^L \underline{\frac{dD_1^d(l)}{dl}}\,\frac{dD_1^{\mathrm{d}}(l)}{dl}\,dl, \tag{91}$$

$$Q_{\underline{sn,s}\mathrm{sn,s}} = k_{\underline{q}\mathrm{q}}\int_0^L \underline{\frac{d(S_1^d(l)-S_1^u(l))}{dl}}\,\frac{d(S_1^{\mathrm{d}}(l)-S_1^{\mathrm{u}}(l))}{dl}\,f_{\underline{sn}\mathrm{sn}}(l)dl, \tag{92}$$

$$Q_{\underline{sh,s}\mathrm{sh,s}} = k_{\underline{q}\mathrm{q}}\int_0^L \underline{\frac{d(S_1^d(l)-S_1^u(l))}{dl}}\,\frac{d(S_1^{\mathrm{d}}(l)-S_1^{\mathrm{u}}(l))}{dl}\,(1-f_{\underline{sn}\mathrm{sn}}(l))dl, \tag{93}$$

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

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

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

where ~~f_d~~ 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 ~~$\overline{A}_{n,x}$~~ $\overline{A}_{\mathrm{n},x}$ can be calculated using the equations described in this section (Eqs. 64 to 94) if ~~$c_{i,x}$~~ $c_{\mathrm{i},x}$ is given.

~~$\overline{A}_{n,x}$~~ $\overline{A}_{\mathrm{n},x}$ 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:

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

where c_a is the partial pressure of atmospheric CO$_2$, ~~$c_{s,x}$~~ $c_{\mathrm{s},x}$ is the partial pressure of CO$_2$ at the leaf boundary layer for sunlit and shade leaves, ~~$\overline{g}_l$~~ $\overline{g}_{\mathrm{l}}$ is the leaf boundary conductance for vapour per unit leaf area, and ~~$\overline{g}_{st,x}$~~ $\overline{g}_{\mathrm{st},x}$ is the stomatal conductance for vapour per unit leaf area for sunlit and shade leaves. From Eq. 95, ~~$c_{i,x}$ and $c_{s,x}$~~ $c_{\mathrm{i},x}$ and $c_{\mathrm{s},x}$ are defined by

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

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

The ~~parameters c_a~~ variables c_{a} and $\overline{g_l}$ are given by

$$c_a = (C_{\underline{a}\mathrm{a,ppm}} * 10^{-6})P_{\underline{a}\mathrm{a}}, \tag{98}$$

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

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

where ~~w_{H_2O}~~ $w_{\mathrm{H_2O}}$ is a constant for the molar weight of vapour, ~~$\overline{g}_a$~~ $\overline{g}_{\mathrm{a}}$ is the leaf boundary conductance for heat per unit leaf area (for both sides of the leaf), ~~c_h~~ c_{h} is the leaf transfer coefficient for heat and is a crop specific parameter, ~~U_c~~ 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 instead of $\overline{g}_a/2$~~ $C_{\mathrm{Hc}}U/L$ instead of $\overline{g}_{\mathrm{a}}/2$ in Eq. 99.

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

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

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

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

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

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

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

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

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

$$\begin{aligned} e_{a\mathrm{a}} &= Q(R_{dry\mathrm{dry}}/R_{vap\mathrm{vap}}), & (105)\\ e_{i\mathrm{i}} &= e_{sat\mathrm{sat}}(T_{c\mathrm{c}},P_{a\mathrm{a}}), & (106)\\ e_{sat\mathrm{sat}}(T_{c\mathrm{c}},P_{a\mathrm{a}}) &= Q_{sat\mathrm{sat}}(T_{c\mathrm{c}},P_{a\mathrm{a}})(R_{dry\mathrm{dry}}/R_{vap\mathrm{vap}}), & (107) \end{aligned}$$

where ~~e_i~~ e_{i} is assumed to be saturated.

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

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

$$\begin{aligned} \overline{g}_{s\mathrm{s}} &= \overline{g}_{st\mathrm{st}}*(T_{c\mathrm{c}}R_{vap\mathrm{vap}}w_{H_2O\mathrm{H_2O}}/P_{a\mathrm{a}}), & (108)\\ \overline{g}_{st\mathrm{st}} &= \{(\overline{g}_{st,sn\mathrm{st,sn}}*L_{sn\mathrm{sn}}+\overline{g}_{st,sh\mathrm{st,sh}}*L_{sh\mathrm{sh}})/L\}*2, & (109) \end{aligned}$$

where ~~$\overline{g}_{st}$~~ $\overline{g}_{\mathrm{st}}$ 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 ~~DVS~~D_{vs}, which is an index used to quantify developmental stage of crops. ~~DVS~~ D_{vs} is mainly used for determining the timing of transplanting, heading, and harvesting. In addition, ~~DVS~~ 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). ~~DVS~~ D_{vs} is calculated from

$$\underline{DVS}D_{\mathrm{vs}} = \underline{GDS}G_{\mathrm{ds}}/\underline{mGDS}G_{\mathrm{ds,m}}, \tag{110}$$

$$\underline{GDS}G_{\mathrm{ds}} = \int_0^t \underline{DVR}D_{\mathrm{vr}}dt', \tag{111}$$

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

where ~~GDS~~ G_{ds} is the growing degree seconds at t, ~~$mGDS$ is GDS~~ $G_{\mathrm{ds,m}}$ is G_{ds} required until maturation, ~~DVR~~ D_{vr} is the development rate at t, T_0 is the melting temperature of water, and ~~T_b, T_h, and T_o~~ T_{b}, T_{h}, and T_{o} are the minimum temperature, maximum temperature, and optimal temperature for development, respectively. The value of ~~$mGDS$~~ $G_{\mathrm{ds,m}}$ is parameterized in Masutomi et al. (2016), and ~~T_b, T_h, and T_o~~ T_{b}, T_{h}, and T_{o} are crop-specific parameters. T_0 is a physical constant (Table 5). It should be noted that ~~$DVS = 0$~~ $D_{\mathrm{vs}} = 0$ represents sowing and ~~$DVS = 1$~~ $D_{\mathrm{vs}} = 1$ represents maturation. Furthermore, we introduce two parameters that represent the timing of emergence (~~$eDVS$~~$D_{\mathrm{vs,e}}$) and heading (~~$hDVS$~~$D_{\mathrm{vs,h}}$). Both ~~$eDVS$ and $hDVS$~~ $D_{\mathrm{vs,e}}$ and $D_{\mathrm{vs,h}}$ are crop-specific parameters. The values of ~~$eDVS$ and $hDVS$~~ $D_{\mathrm{vs,e}}$ 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 seedling, the seedlings enter transplanting shock, which prevents shoot growth (Bouman et al., 2001). In MATCRO-Rice, the transplanting shock period is defined by ~~DVS, where $trDVS$ is DVS~~ D_{vs}, where $D_{\mathrm{vs,tr}}$ is D_{vs} at the time when transplanting shock starts and ~~$teDVS$ is DVS~~ $D_{\mathrm{vs,te}}$ is D_{vs} at which transplanting shock ends. Both ~~$trDVS$ and $teDVS$~~ $D_{\mathrm{vs,tr}}$ 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 leaf, stem, panicle, and root. In addition, the model considers glucose reserves in leaves and starch reserves in stem. All carbon assimilated in leaves through photosynthesis is first stored in 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 leaf. This module is based on MACROS (Penning de Vries et al., 1989).

The dry weights of each organ and reserve are expressed by

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

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

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

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

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

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

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

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

$$S_{glu\,\mathrm{glu}} = A_{n\,\mathrm{n}} C_{CO2,glu\,\mathrm{CO_2,glu}} + R_{M,stc\,\mathrm{m,stc}} C_{stc,glu\,\mathrm{stc,glu}}, \tag{119}$$

where, ~~S_{glu}~~ S_{glu} is the supply of glucose to leaf reserve, ~~A_n~~ A_n is the net carbon assimilation calculated in Eq. 63, and ~~$C_{CO_2,glu}$ and $C_{stc,glu}$~~ $C_{\mathrm{CO_2,glu}}$ 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:

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

where δt is one simulation time step, ~~k_{glu}~~ k_{glu} is the critical ratio at which the partition of glucose happens, and δt is a simulation setting parameter. We set ~~$k_{glu} = 0.1$~~ $k_{\mathrm{glu}} = 0.1$ (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:

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

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

$$
\begin{aligned}
G_{R,lef\,\mathrm{r,lef}} &= G_{P,glu\,\mathrm{p,glu}} P_{R,sh\,\mathrm{r,sh}} P_{R,lef\,\mathrm{r,lef}} C_{glu,lef\,\mathrm{glu,lef}}, && (122)\\
G_{R,stm\,\mathrm{r,stm}} &= G_{P,glu\,\mathrm{p,glu}} P_{R,sh\,\mathrm{r,sh}} (1 - P_{R,lef\,\mathrm{r,lef}} - P_{R,pnc\,\mathrm{r,pnc}})(1 - f_{stc\,\mathrm{stc}}) C_{glu,stm\,\mathrm{glu,stm}}, && (123)\\
G_{R,pnc\,\mathrm{r,pnc}} &= G_{P,glu\,\mathrm{p,glu}} P_{R,sh\,\mathrm{r,sh}} P_{R,pnc\,\mathrm{r,pnc}} C_{glu,pnc\,\mathrm{glu,pnc}}, && (124)\\
G_{R,rot\,\mathrm{r,rot}} &= G_{P,glu\,\mathrm{p,glu}} (1 - P_{R,sh\,\mathrm{r,sh}}) C_{glu,rot\,\mathrm{glu,rot}}, && (125)\\
G_{R,stc\,\mathrm{r,stc}} &= G_{P,glu\,\mathrm{p,glu}} P_{R,sh\,\mathrm{r,sh}} (1 - P_{R,lef\,\mathrm{r,lef}} - P_{R,pnc\,\mathrm{r,pnc}}) f_{stc\,\mathrm{stc}} C_{glu,stc\,\mathrm{glu,stc}}, && (126)\\
G_{R,glu\,\mathrm{r,glu}} &= (k_{glu\,\mathrm{glu}} W_{lef\,\mathrm{lef}} - W_{glu\,\mathrm{glu}})/\delta t, && (127)
\end{aligned}
$$

where ~~$P_{R,sh}$~~ $P_{\mathrm{r,sh}}$ is the ratio of glucose partitioned to shoot, ~~$P_{R,lef}$ and $P_{R,pnc}$~~ $P_{\mathrm{r,lef}}$ and $P_{\mathrm{r,pnc}}$ are the partition ratios of glucose from shoot to leaf and panicle, ~~f_{stc}~~ f_{stc} is the proportion of glucose allocated to starch reserve in stem, ~~$C_{glu,lef}$, $C_{glu,stm}$, $C_{glu,rot}$, $C_{glu,pnc}$, and $C_{glu,stc}$~~ $C_{\mathrm{glu,lef}}$, $C_{\mathrm{glu,stm}}$, $C_{\mathrm{glu,rot}}$, $C_{\mathrm{glu,pnc}}$, and $C_{\mathrm{glu,stc}}$ are dry weight of corresponding organs and reserves that are produced from the unit weight of glucose. ~~f_{stc}, $C_{glu,lef}$, $C_{glu,stm}$, $C_{glu,rot}$, and $C_{glu,pnc}$~~ 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}~~ f_{stc} is parameterized in Masutomi et al. (2016). We set the values of ~~$C_{glu,lef}$, $C_{glu,stm}$, $C_{glu,rot}$, and $C_{glu,pnc}$~~ $C_{\mathrm{glu,lef}}$, $C_{\mathrm{glu,stm}}$, $C_{\mathrm{glu,rot}}$, and $C_{\mathrm{glu,pnc}}$ according to Penning de Vries et al. (1989). ~~$C_{glu,stc}$~~ $C_{\mathrm{glu,stc}}$ 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 leaf. Therefore, the growth rate of each organ and reserve are calculated as follows:

$$
\begin{aligned}
G_{R,lef\,\mathrm{r,lef}} &= G_{R,stm\,\mathrm{r,stm}} = G_{R,rot\,\mathrm{r,rot}} = G_{R,pnc\,\mathrm{r,pnc}} = G_{R,stc\,\mathrm{r,stc}} = 0 && (128)\\
G_{R,glu\,\mathrm{r,glu}} &= S_{glu\,\mathrm{glu}}. && (129)
\end{aligned}
$$

The partition ratios to each organ are given as

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

$$
P_{R,lef\,\mathrm{r,lef}} = \begin{cases} P_{\mathrm{lef}} & (D_{\mathrm{vs}} \le D_{\mathrm{vs,lef1}}) \\ \frac{P_{\mathrm{lef}}(D_{\mathrm{vs,lef2}} - D_{\mathrm{vs}})}{(D_{\mathrm{vs,lef2}} - D_{\mathrm{vs,lef1}})} & (D_{\mathrm{vs,lef1}} < D_{\mathrm{vs}} \le D_{\mathrm{vs,lef2}}), \\ 0 & (\text{Otherwise}) \end{cases} \qquad (131)
$$

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

where ~~DVS_{rot1}, DVS_{rot2}, DVS_{lef1}, DVS_{lef2}, DVS_{pnc1}, and DVS_{pnc2} represent the DVS~~ $D_{\mathrm{vs,rot1}}$, $D_{\mathrm{vs,rot2}}$, $D_{\mathrm{vs,lef1}}$, $D_{\mathrm{vs,lef2}}$, $D_{\mathrm{vs,pnc1}}$, and $D_{\mathrm{vs,pnc2}}$ represent the D_{vs} values at which corresponding partitions change, ~~P_{rot}~~ P_{rot} is the ratio of partitioned glucose to the roots at ~~$DVS < DVS_{rot1}$, and P_{lef}~~ $D_{\mathrm{vs}} < D_{\mathrm{vs,rot1}}$, and P_{lef} is the ratio of glucose partitioned to the leaf and glucose partitioned to shoot at ~~$DVS < DVS_{lef}$. DVS_{rot1}, DVS_{rot2}, DVS_{lef1}, DVS_{lef2}, DVS_{pnc1}, DVS_{pnc2}, P_{rot}, and P_{lef}~~ $D_{\mathrm{vs}} < D_{\mathrm{vs,lef1}}$. $D_{\mathrm{vs,rot1}}$, $D_{\mathrm{vs,rot2}}$, $D_{\mathrm{vs,lef1}}$, $D_{\mathrm{vs,lef2}}$, $D_{\mathrm{vs,pnc1}}$, $D_{\mathrm{vs,pnc2}}$, 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 shoot during transplanting shock (~~$teDVS < DVS \le teDVS$~~ $D_{\mathrm{vs,tr}} < D_{\mathrm{vs}} \le D_{\mathrm{vs,te}}$). It is important to note that transplanting shock is considered only when transplanting is conducted.

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

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

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

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

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

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

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

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

4.4 LAI, crop height, and root depth

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

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

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

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

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

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

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

where ~~Yld~~ Y_{ld} is the crop yield, ~~$W_{pnc,mt}$~~ $W_{\mathrm{pnc,mt}}$ is the dry weight of the panicle at maturity, ~~k_{yld}~~ k_{yld} is the ratio of the crop yield to ~~$W_{pnc,mt}$~~ $W_{\mathrm{pnc,mt}}$. The variable ~~k_{yld}~~ 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 alter globally 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 (Ver. 1) of MATCRO-Rice has a ~~couple of major limitations. First, nitrogen~~ 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.

~~Second, the impact of water stress on crop growth is not considered in MATCRO. This limitation is not considered a problem in irrigated land but in rain-fed land. If the model is applied in rain-fed lands, the model needs to be improved.~~

6 Code availability

The source code of MATCRO will be distributed at 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~~ ρ_a and ~~Q_{sat}~~ Q_sat

The air density (~~ρ_a~~ρ_a) and the specific humidity at saturation (~~Q_{sat}~~Q_sat) are calculated physically according to the equation for the state of dry air and the Clausisu-Clapeyron equation, respectively, as follow:

$$\rho_{a\mathrm{a}} = P_{a\mathrm{a}}/(R_{dry\mathrm{dry}}T_{a\mathrm{a}}), \tag{A1}$$

$$Q_{sat\mathrm{sat}}(T_{xx}, P_{a\mathrm{a}}) = (R_{dry\mathrm{dry}}/R_{vap\mathrm{vap}})\{e_{sat\mathrm{sat}}(T_0)\exp\left((\lambda/R_{vap})(1/T_0-1/T_x)\right)\exp\left((\lambda/R_{\mathrm{vap}})(1/T_0-1/T_x)\right)\}/P_{a\mathrm{a}} \tag{A2}$$

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

Appendix B: Zenith angle θ

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

$$\cos(\theta) = \sin(2\pi L_{\underline{t}\utilde{\mathrm{t}}}/360)\sin(\delta_{\underline{s}\utilde{\mathrm{s}}}) + \cos(2\pi L_{\underline{t}\utilde{\mathrm{t}}}/360)\cos(\delta_{\underline{s}\utilde{\mathrm{s}}})\cos(h_{\underline{arg}\utilde{\mathrm{arg}}}), \tag{B1}$$

$$\delta_{\underline{s}\utilde{\mathrm{s}}} = -\arcsin(\sin(23.45(2\pi/360))\cos(2\pi(D_{\underline{oy}\utilde{\mathrm{oy}}}+10)/365)), \tag{B2}$$

$$h_{\underline{arg}\utilde{\mathrm{arg}}} = 2\pi(h_{\underline{r}\utilde{\mathrm{r}}}-12)/24, \tag{B3}$$

where ~~L_t~~ L_t is the latitude in radians at the simulation site, ~~δ_s~~ δ_s is the declination of the sun, ~~h_{arg}~~ h_arg is the hour angle from noon (~~$h_r = 12$), D_{oy}~~ $h_\mathrm{r} = 12$), D_oy is the number of days from Jan 1 at the simulation site, and ~~h_r~~ 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:

$$a_i = F d_{\underline{f}\utilde{\mathrm{f}}}\{(1-t_{\underline{i}\utilde{i}})^2 - r^2{}_{\underline{i}\utilde{i}}\}^{1/2}, \tag{C1}$$

$$\begin{aligned} C_{1,i} = {} & \{-(A_{2,i}-r_{\underline{g}\utilde{\mathrm{g}}})(S^{\underline{d}}_{\underline{i}}\underline{(0)}{}^{\utilde{\mathrm{d}}}_{\utilde{i}}\utilde{(0)} - C_{3,i}D^{\underline{d}}_{\underline{i}}\underline{(0)}{}^{\utilde{\mathrm{d}}}_{\utilde{i}}\utilde{(0)})\exp(-a_iL) \\ & +(C_{3,i}r_{\underline{g}\utilde{\mathrm{g}}}+r_{\underline{g}\utilde{\mathrm{g}}}-C_{4,i})D^{\underline{d}}_{\underline{i}}\underline{(0)}{}^{\utilde{\mathrm{d}}}_{\utilde{i}}\utilde{(0)}\exp(-FL\sec(\theta)))\}/A_{\underline{3,i}\utilde{3,\mathrm{i}}}, \end{aligned} \tag{C2}$$

$$\begin{aligned} C_{2,i} = {} & \{(A_{1,i}-r_{\underline{g}\utilde{\mathrm{g}}})(S^{\underline{d}}_{\underline{i}}\underline{(0)}{}^{\utilde{\mathrm{d}}}_{\utilde{i}}\utilde{(0)} - C_{3,i}D^{\underline{d}}_{\underline{i}}\underline{(0)}{}^{\utilde{\mathrm{d}}}_{\utilde{i}}\utilde{(0)})\exp(a_iL), \\ & -(C_{3,i}r_{\underline{g}\utilde{\mathrm{g}}}+r_{\underline{g}\utilde{\mathrm{g}}}-C_{4,i})D^{\underline{d}}_{\underline{i}}\underline{(0)}{}^{\utilde{\mathrm{d}}}_{\utilde{i}}\utilde{(0)}\exp(-FL\sec(\theta))\}/A_{\underline{3,i}\utilde{3,\mathrm{i}}}, \end{aligned} \tag{C3}$$

$$C_{3,i} = \sec(\theta)\{t_{\underline{i}\utilde{i}}\sec(\theta)+d_{\underline{f}\utilde{\mathrm{f}}}t_{\underline{i}\utilde{i}}(1-t_{\underline{i}\utilde{i}})+d_{\underline{f}\utilde{\mathrm{f}}}r^2{}_{\underline{i}\utilde{i}}\}/\{d_f^2((1-t_{\underline{i}\utilde{i}})^2-r^2{}_{\underline{i}\utilde{i}})-\sec^2(\theta)\}, \tag{C4}$$

$$C_{4,i} = \{r_{\underline{i}\utilde{i}}(d_{\underline{f}\utilde{\mathrm{f}}}-\sec(\theta))\sec(\theta))\}/\{d_f^2((1-t_{\underline{i}\utilde{i}})^2-r^2{}_{\underline{i}\utilde{i}})-\sec^2(\theta)\}, \tag{C5}$$

$$A_{1,i} = (1-t_{\underline{i}\utilde{i}}+\{(1-t_{\underline{i}\utilde{i}})^2-r^2{}_{\underline{i}\utilde{i}}\}^{1/2})/r_{\underline{i}\utilde{i}}, \tag{C6}$$

$$A_{2,i} = (1-t_{\underline{i}\utilde{i}}-\{(1-t_{\underline{i}\utilde{i}})^2-r^2{}_{\underline{i}\utilde{i}}\}^{1/2})/r_{\underline{i}\utilde{i}}, \tag{C7}$$

$$A_{\underline{3,i}\utilde{3,\mathrm{i}}} = (A_{1,i}-r_{\underline{g}\utilde{\mathrm{g}}})\exp(a_iL)-(A_{2,i}-r_{\underline{g}\utilde{\mathrm{g}}})\exp(-a_iL), \tag{C8}$$

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~~ d_f is a scattering factor, ~~$A_{3,i}$~~ $A_{3,\mathrm{i}}$ is a new variable introduced in Eqs. C2 and C3, L is the LAI, ~~r_g~~ r_g is the surface albedo for shortwave radiation, ~~$D_i^d(0)$ and $S_i^d(0)$~~ $D_i^\mathrm{d}(0)$ and $S_i^\mathrm{d}(0)$ 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~~ d_f is $\sec(2\pi(53/360))$ (Watanabe and Ohtani, 1995). ~~$A_{3,i}$~~ $A_{3,\mathrm{i}}$ is defined in Eq. C8, L is calculated in the CGM (Eq. 137), and ~~r_g for surface water~~ r_g for surface is given in Maruyama and Kuwagata (2010). ~~$D_i^d(0)$ and $S_i^d(0)$~~ $D_i^\mathrm{d}(0)$ and $S_i^\mathrm{d}(0)$ are given in Eqs. 15 and 16, respectively, and θ is calculated in 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 ~~$A_{3,i}$~~ $A_{3,\mathrm{i}}$ 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_{Mw}~~ $d, z_M, z_T, z_{\mathrm{Q}}, z_{\mathrm{Mg}}$, ~~$z_{Tw}$,~~ and ~~$z_{Qw}$~~ 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~~ z_{M}, z_{T}, and z_{Q}), and roughness lengths that express the effect of surface ~~water~~ on the profiles of momentum ~~, temperature, and specific humidity (z_{Mw}, z_{Tw}, and z_{Qw}~~ and temperature (z_{Mg} and z_{Tg}) are calculated according to Watanabe (1994) as follows.

$$
\begin{aligned}
d &= h_{\underline{gt}\utilde{\mathrm{gt}}}\left[1-\frac{1}{A^+}\{1-\exp(-A^+)\}\right],\\
\left(\underline{\ln\frac{h_{gt}-d}{z_M}}\utilde{\ln\frac{h_{\mathrm{gt}}-d}{z_{\mathrm{M}}}}\right)^{-1} &= \left\{1-\exp(-A^+)+\left(\underline{-\ln\frac{z_{Ms}}{h_{gt}}}\utilde{\ln\frac{z_{\mathrm{Ms}}}{h_{\mathrm{gt}}}}\right)^{-1/0.45}\exp(-2A^+)\right\}^{0.45},\\
\left(\underline{\ln\frac{h_{gt}-d}{z_M}}\utilde{\ln\frac{h_{\mathrm{gt}}-d}{z_{\mathrm{M}}}}\right)^{-1}\left(\underline{\ln\frac{h_{gt}-d}{z_X}}\utilde{\ln\frac{h_{\mathrm{gt}}-d}{z_X}}\right)^{-1} &= C^{\infty}{}_{\underline{X}\utilde{X}}\left\{1-\underline{\exp(-P_{3X}A^+)+\left(\frac{C_X^0}{C_X^\infty}\right)^{1/0.9}}\utilde{\exp(-P_{3X}A^+)+\left(\frac{C_X^0}{C_X^\infty}\right)^{1/}}\right.\\
\left(\underline{\ln\frac{h_{gt}-d}{z_{Mw}}}\utilde{\ln\frac{h_{\mathrm{gt}}-d}{z_{\mathrm{Mg}}}}\right)^{2} &= \left(\underline{\ln\frac{h_{gt}-d}{z_M}}\utilde{\ln\frac{h_{\mathrm{gt}}-d}{z_M}}\right)\left(\underline{\ln\frac{h_{gt}-d}{z_M^+}}\utilde{\ln\frac{h_{\mathrm{gt}}-d}{z_M^+}}\right),\\
\left(\underline{\ln\frac{h_{gt}-d}{z_{Mw}}}\utilde{\ln\frac{h_{\mathrm{gt}}-d}{z_{\mathrm{Mg}}}}\right)\left(\underline{\ln\frac{h_{gt}-d}{z_{Xw}}}\utilde{\ln\frac{h_{\mathrm{gt}}-d}{z_{T\mathrm{g}}}}\right) &= \left(\underline{\ln\frac{h_{gt}-d}{z_M}}\utilde{\ln\frac{h_{\mathrm{gt}}-d}{z_M}}\right)\left(\underline{\ln\frac{h_{gt}-d}{z_X^+}}\utilde{\ln\frac{h_{\mathrm{gt}}-d}{z_T^+}}\right),\\
A^+ &= \underline{\frac{c_mL}{2\kappa^2}}\utilde{\frac{c_{\mathrm{m}}L}{2\kappa^2}},\\
C^0{}_{\underline{X}\utilde{X}} &= \left(\underline{\ln\frac{h_{gt}-d}{z_M}}\utilde{\ln\frac{h_{\mathrm{gt}}-d}{z_{\mathrm{M}}}}\right)^{-1}\left(\underline{\ln\frac{h_{gt}-d}{z_X^+}}\utilde{\ln\frac{h_{\mathrm{gt}}-d}{z_X^+}}\right)^{-1},\\
C^{\infty}{}_{\underline{X}\utilde{X}} &= \underline{\frac{-1+(1+8F_X)^{0.5}}{2}}\utilde{\frac{-1+(1+8F_X)^{0.5}}{2}},\\
F_{\underline{X}\utilde{X}} &= \underline{\frac{c_X}{c_m}}\utilde{\frac{c_X}{c_{\mathrm{m}}}},\\
\left(\underline{\ln\frac{h_{gt}-d}{z_*^+}}\utilde{\ln\frac{h_{\mathrm{gt}}-d}{z_*^+}}\right)^{-1} &= \underline{\frac{1}{-\ln\left(\frac{z_{*s}}{h_{gt}}\right)}}\utilde{\frac{1}{-\ln\left(\frac{z_{*\mathrm{s}}}{h_{\mathrm{gt}}}\right)}}\left(\frac{P_{1*}}{P_{1*}+A^+\exp(A^+)}\right)^{P_{2*}},\\
P_{1*} &= 0.00115\left(\underline{\frac{z_{*s}}{h_{gt}}}\utilde{\frac{z_{*\mathrm{s}}}{h_{\mathrm{gt}}}}\right)^{0.1}\underline{\exp\left\{5\left(\frac{z_{*s}}{h_{gt}}\right)\right\}}\utilde{\exp\left\{5\left(\frac{z_{*\mathrm{s}}}{h_{\mathrm{gt}}}\right)\right\}},\\
P_{2*} &= 0.55\underline{\exp\left\{-0.58\left(\frac{z_{*s}}{h_{gt}}\right)^{0.35}\right\}}\utilde{\exp\left\{-0.58\left(\frac{z_{*\mathrm{s}}}{h_{\mathrm{gt}}}\right)^{0.35}\right\}},\\
P_{3X} &= \{F_{\underline{X}\utilde{X}}+0.084\underline{\exp(-15F_X)}\utilde{\exp(-15F_X)}\}^{0.15},\\
P_{4X} &= 2F_X^{1.1},\\
c_{\underline{e}\mathrm{e}} &= c_{\underline{h}\mathrm{h}}/(1+c_{\underline{h}\mathrm{h}}(U_{\underline{c}\mathrm{c}}/\overline{g}_{\underline{s}\mathrm{s}})).
\end{aligned}
$$

Here, ~~z_{Ms}, z_{Ts}, and z_{Qs}~~ $z_{\mathrm{Ms}}, z_{\mathrm{Ts}}$, and z_{Qs} are the roughness lengths of surface ~~water~~ for momentum, temperature, and specific humidity, respectively. In this model, we assume ~~z_{Ms}, z_{Ts}, and $z_{Qs} = 0.001$~~ $z_{\mathrm{Ms}}, z_{\mathrm{Ts}}$, and $z_{\mathrm{Qs}} = 0.001$ m (Kimura and Kondo, 1998). ~~c_m, c_h, and c_e~~ c_{m}, c_{h}, and c_{e} are the leaf transfer coefficients for momentum, temperature, and specific humidity, respectively. ~~c_m an c_h~~ c_{m} an c_{h} are crop-specific parameters, while ~~c_e~~ c_{e} is calculated in Eq. E15. ~~h_{gt}~~ h_{gt} and L are crop height and LAI, respectively, and are calculated in the CGM (Eqs. 139 and 137). ~~$\overline{g}_s$~~ $\overline{g}_{\mathrm{s}}$ is the stomatal conductance per unit leaf area for both sides of the leaf (Eq. 108). ~~U_c~~ 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^+~~ C_{X}^0, C_{X}^∞, z_{M}^+, z_{X}^+, z_*^+, P_{1*}, P_{2*},P_{3X}, P_{4X}, ~~F_X~~ F_{X} are the intermediate variables, and κ is the Karman constant. The symbol "$*$" indicates "M", "T", or "Q", and the symbol "~~X~~X" indicates "T" or "Q".

Appendix F: Mean wind speed in the canopy

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

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

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

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

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

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Table 1. Meteorological inputs

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

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

Variable	Unit	Description
LSM to CGM		
~~$R_\mathrm{I}^d(l)$~~ $D_\mathrm{I}^\mathrm{d}(l)$	W m^{-2}	direct downward radiant flux density for photosynthesis active radiation (PAR) at a leaf area index (LAI) depth of l
~~$S_\mathrm{I}^d(l)$~~ $S_\mathrm{I}^\mathrm{d}(l)$	W m^{-2}	scattered downward radiant flux density for PAR at a LAI depth of l
~~$S_\mathrm{I}^u(l)$~~ $S_\mathrm{I}^\mathrm{u}(l)$	W m^{-2}	scattered upward radiant flux density for PAR at a LAI depth of l
~~T_c~~ T_c	K	canopy temperature
CGM to LSM		
~~$\bar{g}_s$~~ $\bar{g}_\mathrm{s}$	m s^{-1}	stomatal conductance per unit leaf area for both sides of the leaf
~~h_{gt}~~ h_gt	m	canopy height
L	m^2 m^{-2}	LAI
~~W_{sh}~~ W_sh	kg ha^{-1}	dry matter weight of shoot
~~z_{rt}~~ 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)	$[1/C_{\mathrm{Hc}} + U/(\bar{g}_{\mathrm{st}} L/2)]^{-1}$
31 and 32	Campbell and Norman (1998)	Unknown
36	Maruyama and Kuwagata (2008)	$\frac{\Theta_0 C_M^{3/2} U^2}{\kappa g C_{\mathrm{Hg}} (T_{\mathrm{g}} - T_{\mathrm{a}})}$
37	Campbell and Norman (1998)	300K
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 ($z_{\mathrm{b}} < z \leq z_{\mathrm{max}}$)	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

Table 4: Variables

Symbol	Units	Eq.	Description
~~$\overline{A}_{g,x}$~~ $\overline{A}_{\mathrm{g},x}$	mol(CO$_2$) m^{-2}(l)s^{-1}	68	gross primary production pe shade(~~$\overline{A}_{g,sh}$~~$\overline{A}_{\mathrm{g,sh}}$) leaves
~~$\overline{A}_{g',x}$~~ $\overline{A}_{\mathrm{g}',x}$	mol(CO$_2$) m^{-2}(l)s^{-1}	72	gross primary production with area of sunlit (~~$\overline{A}_{g',sn}$~~$\overline{A}_{\mathrm{g}',\mathrm{sn}}$)
~~A_n~~ A_{n}	mol(CO$_2$) m^{-2}s^{-1}	63	net carbon assimilation
~~$\overline{A}_{n,x}$~~ $\overline{A}_{\mathrm{n},x}$	mol(CO$_2$) m^{-2}(l) s^{-1}	64	net carbon assimilation per u (~~$\overline{A}_{n,sh}$~~$\overline{A}_{\mathrm{n,sh}}$) leaves
$A_{3,i}$	-	C8	variable for the calculation of c
A^+	-	E6	intermediate variable for the ca
~~C_E~~ C_{E}	-	28	BTC for latent heat between th
~~C_{Ec}~~ C_{Ec}	-	25	bulk transfer coefficients (BTC
~~C_{Ew}~~ C_{Eg}	-	24	BTC for latent heat between su
~~C_{Hc}~~ C_{H}	-	29	BTC for sensible heat between
C_{Hc}	-	27	BTC for sensible heat between
~~C_{Hw}~~ C_{Hg}	-	26	BTC for sensible heat between
~~C_M~~ C_{M}	-	38	BTC for momentum between th
~~C_{Mw}~~ C_{Mg}	-	39	BTC for momentum between s
$C_{x,i}$	-	C2 to C5	coefficients of radiation equatio
~~C_X^0~~ C_{X}^0	-	E7	intermediate variable for the ca
~~C_X^∞~~ C_{X}^∞	-	E8	intermediate parameter for the
~~c_a~~ c_{a}	Pa	98	partial pressure of atmospheric
~~c_e~~ c_{e}	-	E15	leaf transfer coefficient for spec
~~$c_{hs}(z)$~~ $c_{\mathrm{hs}}(z)$	J m^{-3} K^{-1}	50	volumetric heat capacity of soil
~~$c_{i,x}$~~ $c_{\mathrm{i},x}$	Pa	64 to 107	partial pressure of intercellular
~~$c_{s,x}$~~ $c_{\mathrm{s},x}$	Pa	97	partial pressure of CO$_2$ at leaf

continued

Symbol	Units	Eq.	Description
~~$D_i^d(l)$~~ $D_i^{\mathrm{d}}(l)$	$\mathrm{W\,m^{-2}}$	12	radiant flux density for downwa ation (PAR) ($i=1$) or near inf (LAI) depth of l
~~D_g~~ D_{g}	$\mathrm{kg\,m^{-2}\,s^{-1}}$	44	amount of water that falls from
~~D_{oy}~~ D_{oy}	day	-	the number of days from Jan 1
~~DVR~~ D_{vr}	K	112	development rate at t
~~DVS~~ D_{vs}	-	110	development stage at t
d	m	E1	zero-plane displacement height
~~E_c~~ E_{c}	$\mathrm{kg\,m^{-2}\,s^{-1}}$	7	evaporation from canopy
~~E_t~~ $E_{\mathrm{c,max}}$	$\mathrm{kg\,m^{-2}\,s^{-1}}$	~~8~~ 7	~~transpiration~~ maximum evapora
~~E_w~~ E_{g}	$\mathrm{kg\,m^{-2}\,s^{-1}}$	9	evaporation from surface ~~water~~
~~e_a~~ $E_{\mathrm{g,max}}$	$\mathrm{kg\,m^{-2}\,s^{-1}}$	62	maximum evaporation from sur
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 ca
e_{a}	P_a	105	atmospheric vapour pressure
~~e_i~~ e_{i}	P_a	106	vapour pressure in leaf
~~e_{sat}~~ e_{sat}	P_a	107	saturated vapour pressure
~~$e_{s,x}$~~ $e_{\mathrm{s},x}$	P_a	103	vapour pressure at leaf boundar leaves
~~$F_s(z)$~~ F_{c}	$\mathrm{kg\,m^{-2}\,s^{-1}}$	46	amount of water that falls fron surface
$F_{\mathrm{s}}(z)$	$\mathrm{m^3\,m^{-2}\,s^{-1}}$	~~??~~55	water flux at a soil depth of ~~z~~ z
~~F_X~~ F_{X}	-	E9	intermediate parameter for the c
~~f_{cw}~~ f_{cw}	-	40	fraction of canopy that is wet
~~f_{df}~~ f_{df}	-	17	fraction of scattered radiation
~~f_{dwn}~~ f_{dwn}	-	69	factor of photosynthesis down-r
~~f_{int}~~ f_{int}	-	43	interception efficiency of precip
~~GDS~~ $f_{\mathrm{r}}(z)$	-	59	root distribution at a soil depth
$f_{\mathrm{s}}(z)$	-	79	water stress function on photos
f_{v}	-	78	water stress factor on photosynt
G_{ds}	$\mathrm{K\cdot s}$	111	growing degree seconds at t_s
~~$G_{P,glu}$~~ $G_{\mathrm{p,glu}}$	$\mathrm{kg\,ha^{-1}s^{-1}}$	127 and 129	glucose partitioned to each orga
~~$G_{R,glu}$~~ $G_{\mathrm{r,glu}}$	$\mathrm{kg\,ha^{-1}s^{-1}}$	127 and 129	growth rate of glucose reserves
~~$G_{R,pnc}$~~ $G_{\mathrm{r,pnc}}$	$\mathrm{kg\,ha^{-1}\,s^{-1}}$	124 and 128	growth rate of dry weight for pa
~~$G_{R,rot}$~~ $G_{\mathrm{r,rot}}$	$\mathrm{kg\,ha^{-1}\,s^{-1}}$	125 and 128	growth rate of dry weight for ro
~~$G_{R,lef}$~~ $G_{\mathrm{r,lef}}$	$\mathrm{kg\,ha^{-1}\,s^{-1}}$	122 and 128	growth rate of dry weight for le
~~$G_{R,stc}$~~ $G_{\mathrm{r,stc}}$	$\mathrm{kg\,ha^{-1}s^{-1}}$	126 and 128	growth rate of dry weight for st
~~$G_{R,stm}$~~ $G_{\mathrm{r,stm}}$	$\mathrm{kg\,ha^{-1}\,s^{-1}}$	123 and 128	growth rate of dry weight for st
~~$G_s(z)$~~ $G_{\mathrm{s}}(z)$	$\mathrm{W\,m^{-2}}$	49	heat flux at a soil depth of ~~z~~z
~~G_{ws}~~ G_{gs}	$\mathrm{W\,m^{-2}}$	10	heat flux from surface ~~water~~ to
~~$\overline{g}_a$~~ $\overline{g}_{\mathrm{a}}$	$\mathrm{m\,s^{-1}}$	100	leaf boundary conductance per
~~$\overline{g}_l$~~ $\overline{g}_{\mathrm{l}}$	$\mathrm{mol\,m^{-2}}(l)\,\mathrm{s^{-1}}$	99	leaf boundary conductance for
~~$\overline{g}_s$~~ $\overline{g}_{\mathrm{s}}$	$\mathrm{m\,s^{-1}}$	108	stomatal conductance per unit l
~~$\overline{g}_{st}$~~ $\overline{g}_{\mathrm{st}}$	$\mathrm{mol\,m^{-2}}(l)\,\mathrm{s^{-1}}$	109	stomatal conductance for vapou
~~$\overline{g}_{st,x}$~~ $\overline{g}_{\mathrm{st},x}$	$\mathrm{mol\,m^{-2}}(l)\,\mathrm{s^{-1}}$	101	stomatal conductance for vapo shade (~~$\overline{g}_{st,sh}$~~$\overline{g}_{\mathrm{st,sh}}$) leaves
~~H_c~~ H_{c}	$\mathrm{W\,m^{-2}}$	5	sensible heat flux from canopy
~~H_w~~ H_{g}	$\mathrm{W\,m^{-2}}$	6	sensible heat flux from surface
~~h_{gt}~~ h_{gt}	m	139	canopy height
~~h_{arg}~~ h_{arg}	rad	B3	hour angle from noon (~~h_r~~ h_{r} =

continued

Symbol	Units	Eq.	Description
~~h_r~~ h_{ms}	-	60	humidity of topsoil
h_{r}	hour	-	local time at the simulation site
~~$h_{s,x}$~~ $h_{\mathrm{s},x}$	$\mathrm{P}_a\ \mathrm{P}_a^{-1}$	102	relative humidity at leaf b (~~$h_{s,sh}$~~$h_{\mathrm{s,sh}}$) leaves
~~I_c~~ I_{c}	kg m^{-2} s^{-1}	42	amount of precipitation intercep
$K(z)$	kg s m^{-3}	56	hydraulic conductivity at a soil
~~K_c~~ K_{c}	Pa	85	Michaelis constant for $\mathrm{CO_2}$ fix
~~$K_e(z)$~~ $K_{\mathrm{e}}(z)$	-	52	the Kersten number
~~K_O~~ K_{O}	Pa	86	Michaelis constant for $\mathrm{O_2}$ inhib
~~$k_{ts}(z)$~~ $k_{\mathrm{ts}}(z)$	W m^{-1} K^{-1}	51	thermal conductivity at a soil de
L	m^2 m^{-2}	137	LAI
~~L_{MO}~~ L_{MO}	m	35	Monin-Obukhov length of the e
~~L_{MOw}~~ L_{MOg}	m	36	Monin-Obukhow length of surf
~~$L_{S,lef}$~~ $L_{\mathrm{s,lef}}$	kg ha^{-1} s^{-1}	133	loss rate of dry weight for leave
~~L_{sn}~~ L_{sn}	$\mathrm{m}^2(l)$ m^{-2}	65	LAI for sunlit leaves
~~L_{sh}~~ L_{sh}	$\mathrm{m}^2(l)$ m^{-2}	66	LAI for shade leaves
l	$\mathrm{m}^2(l)$ m^{-2}	-	LAI depth from the top of cano
~~$P_{R,sh}$~~ $P_{\mathrm{r,sh}}$	-	130	ratio of glucose partitioned to s
~~$P_{R,pnc}$~~ $P_{\mathrm{r,pnc}}$	-	132	ratio of glucose partitioned to p
~~$P_{R,lef}$~~ $P_{\mathrm{r,lef}}$	-	131	ratio of glucose partitioned to l
P_{1*}	-	E11	intermediate variable for the cal
P_{2*}	-	E12	intermediate variable for the cal
P_{3X}	-	E13	intermediate parameter for the
P_{4X}	-	E13	intermediate parameter for the
~~Q_{sat}~~ Q_{sat}	Kg Kg^{-1}	A2	specific humidity at saturation
~~Q_{sn}~~ Q_{sn}	mol m^{-2} s^{-1}	89	photon flux density for PAR ab
~~$Q_{sn,d}$~~ $Q_{\mathrm{sn,d}}$	mol m^{-2} s^{-1}	91	direct PAR absorbed in sunlit l
~~$Q_{sn,s}$~~ $Q_{\mathrm{sn,s}}$	mol m^{-2} s^{-1}	92	scattered PAR absorbed in shad
~~Q_{sh}~~ Q_{sh}	mol m^{-2} s^{-1}	90	photon flux density for PAR ab
~~$Q_{sh,s}$~~ $Q_{\mathrm{sh,s}}$	mol m^{-2} s^{-1}	93	scattered PAR absorbed in shad
~~$\overline{Q}_x$~~ $\overline{Q}_x$	mol $\mathrm{m}^{-2}(l)$ s^{-1}	88	photon flux density for PAR a (~~$\overline{Q}_{sh}$~~$\overline{Q}_{\mathrm{sh}}$) leaves
~~$\overline{R}_{d,x}$~~ q_{t}	-	80	function that represents tempera
$\overline{R}_{\mathrm{d},x}$	$\mathrm{mol(CO_2)}$ $\mathrm{m}^{-2}(l)$ s^{-1}	94	respiration in sunlit (~~$\overline{R}_{d,sn}$~~$\overline{R}$
~~R_{ex}~~ R_{ex}	W m^{-2}	19	extraterrestrial radiation
~~$R_{M,stc}$~~ $R_{\mathrm{m,stc}}$	kg ha^{-1} s^{-1}	134	remobilization rate of dry weig
~~R_{nc}~~ R_{nc}	W m^{-2}	3	net radiant flux density at canop
~~R_{nw}~~ R_{ng}	W m^{-2}	4	net radiant flux density at surfa
~~$R_l^d(l)$~~ $R_{\mathrm{l}}^{\mathrm{d}}(l)$	W m^{-2}	21	radiant flux density for downwa
~~$R_s^d(l)$~~ $R_{\mathrm{s}}^{\mathrm{d}}(l)$	W m^{-2}	21	radiant flux density for downwa
~~$R_s^u(l)$~~ $R_{\mathrm{s}}^{\mathrm{u}}(l)$	W m^{-2}	21	radiant flux density for upward
~~$r_{dd,lef}$~~ $r_{\mathrm{dd,lef}}$	s^{-1}	135	ratio of dead leaf
r_{ij}	-	D1 and D2	reflectivity of canopies ($i = 1$:
r_{s}	-	30	resistance of topsoil to evaporat
S	-	87	Ratio of RuBP partitioned to ca
~~$S_i^d(l)$~~ $S_i^{\mathrm{d}}(l)$	W m^{-2}	13	radiant flux density for downwa 2) at a LAI depth of l
~~$S_i^u(l)$~~ $S_i^{\mathrm{u}}(l)$	W m^{-2}	14	radiant flux density for upward at a LAI depth of l
~~S_{glu}~~ S_{glu}	kg ha^{-1} s^{-1}	119	supply of glucose to the reserve

continued

Symbol	Units	Eq.	Description
~~SLW~~ S_{lw}	kg $\mathrm{m}^{-2}(l)$	138	specific leaf area
~~$S_s(z)$~~ $S_{\mathrm{s}}(z)$	$\mathrm{m}^3\ \mathrm{m}^{-3}\ \mathrm{s}^{-1}$	58	absorption for transpiration by
~~S_{tw}~~ S_{tw}	W m^{-2}	11	heat flux stored in surface wate
~~T_c~~ T_{c}	K	3 to 11	canopy temperature
~~$T_s(z)$~~ $T_{\mathrm{s}}(z)$	K	48	soil temperature at ~~z of soil dep~~
~~T_x~~ T_x	K	A2	temperature of canopy (~~T_c~~ T_{c})
~~T_w~~ T_{g}	K	3 to 11	surface ~~water~~ temperature
t	s	-	time
~~t_e~~ t_{e}	s	-	time at emergence after sowing
~~U_c~~ U_{c}	m s^{-1}	F1	wind speed in the canopy
~~U_h~~ U_{h}	m s^{-1}	F2	reference wind speed
~~$V_{max}(l)$~~ $V_{\mathrm{max}}(l)$	mol($\mathrm{CO_2}$) $\mathrm{m}^{-2}(l)\ \mathrm{s}^{-1}$	83	reference value for maximum R
~~$\overline{V}_{max,x}$~~ $\overline{V}_{\mathrm{max},x}$	mol($\mathrm{CO_2}$) $\mathrm{m}^{-2}(l)\ \mathrm{s}^{-1}$	81 and 82	reference value for maximum shade leaves
~~$\overline{V}_{mc,x}$~~ $\overline{V}_{\mathrm{mc},x}$	mol($\mathrm{CO_2}$) $\mathrm{m}^{-2}(l)\ \mathrm{s}^{-1}$	76	maximum Rubisco capacity pe shade (~~$\overline{V}_{mc,sh}$~~ $\overline{V}_{\mathrm{mc,sh}}$) leave
~~$\overline{V}_{ms,x}$~~ $\overline{V}_{\mathrm{ms},x}$	mol($\mathrm{CO_2}$) $\mathrm{m}^{-2}(l)\ \mathrm{s}^{-1}$	77	maximum Rubisco capacity pe shade (~~$\overline{V}_{ms,sh}$~~ $\overline{V}_{\mathrm{ms,sh}}$) leave
~~W_{glu}~~ W_{glu}	kg ha^{-1}	118	dry weight of glucose reserves
~~W_{pnc}~~ W_{pnc}	kg ha^{-1}	115	dry weight of panicles
~~$W_{pnc,mt}$~~ $W_{\mathrm{pnc,mt}}$	kg ha^{-1}	-	dry weight of panicles at matur
~~W_{rot}~~ W_{rot}	kg ha^{-1}	116	dry weight of roots
~~W_{sh}~~ W_{sh}	kg ha^{-1}	136	dry weight of shoot
~~W_{stc}~~ W_{stc}	kg ha^{-1}	117	dry weight of starch reserves in
~~W_{stm}~~ W_{stm}	kg ha^{-1}	114	dry weight of stems
~~w_c~~ w_{c}	m	41	amount of water stored in cano
~~w_{cap}~~ w_{cap}	m	45	canopy water capacity
~~$w_s(z)$~~ $w_{\mathrm{s}}(z)$	$\mathrm{m}^3\ \mathrm{m}^{-3}$	~~?? and ??~~53	volumetric concentration of soi
~~Yld~~ Y_{ld}	kg ha^{-1}	141	crop yield
z	m	-	soil depth
~~z_M~~ z_{M}	m	E2	roughness length of the entire s
~~z_{Mw}~~ z_{Mg}	m	E4	roughness length that express th tum
~~z_M^+~~ z_{M}^+	m	E10	intermediate variable for the ca
~~z_Q~~ z_{Q}	m	E3	roughness length of the entire s
~~z_{Qw}~~ z_{rt}	m	~~E5roughness length that express the effect of water surface on the profile of specific humidity z_{rt} m~~140	root depth
~~z_T~~ z_{T}	m	E3	roughness length of the entire s
~~z_{Tw}~~ z_{Tg}	m	E5	roughness length that express th ature
~~z_X^+~~ z_{X}^+	m	E10	intermediate variable for the ca
z_*^+	m	E10	intermediate variable for the cal
~~δ_s~~ δ_{s}	rad	B2	declination of the sun
Γ^*	Pa	84	light compensation point
~~γ_m~~ γ_{m}	-	F3	coefficient of exponential decre
~~$\overline{\omega}_{c,x}$~~ $\overline{\omega}_{\mathrm{c},x}$	mol($\mathrm{CO_2}$) $\mathrm{m}^{-2}(l)\ \mathrm{s}^{-1}$	73	Rubisco limited assimilation i leaves
~~$\overline{\omega}_{e,x}$~~ $\overline{\omega}_{\mathrm{e},x}$	mol($\mathrm{CO_2}$) $\mathrm{m}^{-2}(l)\ \mathrm{s}^{-1}$	74	light-limited assimilation in sun
~~$\overline{\omega}_{p,x}$~~ $\overline{\omega}_{\mathrm{p},x}$	mol($\mathrm{CO_2}$) $\mathrm{m}^{-2}(l)\ \mathrm{s}^{-1}$	71	Rubisco and light-limited as (~~$\overline{\omega}_{p,sh}$~~ $\overline{\omega}_{\mathrm{p,sh}}$) leaves

continued

Symbol	Units	Eq.	Description
~~$\overline{\omega}_{s,x}$~~ $\overline{\omega}_{\mathrm{s},x}$	mol(CO$_2$) m$^{-2}(l)$ s^{-1}	75	sucrose limited assimilation fo leaves
~~Ψ_E~~ Ψ_{E}	-	32	diabatic correction factor for va
~~Ψ_H~~ Ψ_{H}	-	32	diabatic correction factor for he
~~Ψ_M~~ Ψ_{M}	-	31	diabatic correction factor for m
$\psi(z)$	J kg^{-1}	57	water potential at a soil depth o
~~ρ_a~~ ϱ_{a}	kg m^{-3}	A1	air density
~~τ_{atm}~~ τ_{atm}	-	18	transmissivity of atmosphere
~~τ_{cs}~~ τ_{cs}	-	20	transmissivity of canopy for sho
~~τ_{cl}~~ τ_{cl}	-	23	transmissivity of canopy for lor
τ_{ij}	-	D3 and D4	transmissivity of canopy ($i = 1$
Θ_0	K	37	potential temperature
θ	rad	B1	zenith angle of the sun
ζ	-	33	atmospheric stability between t
~~ζ_w~~ ζ_{g}	-	34	atmospheric stability between s

Table 5. Physical and chemical constants

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

Table 6: Parameters

Variable	Value	Units	Description	Source
Simulation setting				
~~C_a~~ $C_{\mathrm{a,ppm}}$	-	ppm	atmospheric CO$_2$ concentration	Masutomi et al. (2016)
~~d_w~~ $D_{\mathrm{oy,Ie}}$	-	~~m~~ DOY	~~depth of surface water~~ DOY of the day that irrigation and flooded surface end	Masutomi et al. (2016)
~~L_t~~ $D_{\mathrm{oy,Is}}$	-	~~degree~~DOY	~~latitude of the simulation site~~ DOY of the day that irrigation and flooded surface start	Masutomi et al. (2016)
~~Sw_{DOY}~~ $D_{\mathrm{oy,sw}}$	-	DOY	DOY of sowing day	Masutomi et al. (2016)
~~$W_{glu,0}$~~ d_{w}	-	m	depth of surface water	Masutomi et al. (2016)
L_{t}	-	degree	latitude of the simulation site	Masutomi et al. (2016)
$W_{\mathrm{glu,0}}$	-	kg/ha	dry weight of glucose reserve at emergence	Masutomi et al. (2016)
~~$W_{lef,0}$~~ $W_{\mathrm{lef,0}}$	-	kg/ha	dry weight of leaf at emergence	Masutomi et al. (2016)
~~$W_{rot,0}$~~ $W_{\mathrm{rot,0}}$	-	kg/ha	dry weight of root at emergence	Masutomi et al. (2016)
~~$W_{stm,0}$~~ $W_{\mathrm{stm,0}}$	-	kg/ha	dry weight of stem at emergence	Masutomi et al. (2016)
~~z_a~~ z_{a}	-	m	reference height at which wind speed is observed	Masutomi et al. (2016)
~~z_{max}~~ z_{max}	-	m	depth of soil layer	Masutomi et al. (2016)
~~z_{sat}~~ z_{t}	-	m	depth ~~to which soil is saturated~~ of the soil surface layer	Masutomi et al. (2016)
~~z_b~~ z_{b}	-	m	depth from the soil surface to the upper bound of the bottommost 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~~ K_{s}	-	kg s m^{-3}	hydraulic conductivity at saturation	Masutomi et al. (2016)
~~w_{sat}~~ w_{sat}	-	m^3 m^{-3}	volumetric concentration of soil water at saturation	Masutomi et al. (2016)
~~ψ_s~~ 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~~ 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)
~~$C_{glu,lef}$~~ $C_{\mathrm{glu,lef}}$	0.955	kg ha^{-1}/(kg ha^{-1})	conversion factor of dry weight from glucose to leaf	Penning de Vries et al. (198
~~$C_{glu,pnc}$~~ $C_{\mathrm{glu,pnc}}$	0.821	kg ha^{-1}/(kg ha^{-1})	conversion factor of dry weight from glucose to panicle	Penning de Vries et al. (198
~~$C_{glu,rot}$~~ $C_{\mathrm{glu,rot}}$	0.928	kg ha^{-1}/(kg ha^{-1})	conversion factor of dry weight from glucose to root	Penning de Vries et al. (198
~~$C_{glu,stm}$~~ $C_{\mathrm{glu,stm}}$	0.928	kg ha^{-1}/(kg ha^{-1})	conversion factor of dry weight from glucose to stem	Penning de Vries et al. (198
~~c_h~~ c_{h}	0.06	-	leaf transfer coefficient for heat	Kimura and Kondo (1998)
~~c_m~~ c_{m}	0.2	-	leaf transfer coefficient for momentum	Kimura and Kondo (1998)
~~DVS_{rot1}~~ $D_{\mathrm{vs,rot1}}$	Parameterized	-	1st point of ~~DVS~~ D_{vs} at which the partition to root changes	Masutomi et al. (2016)
~~DVS_{rot2}~~ $D_{\mathrm{vs,rot2}}$	Parameterized	-	2nd point of ~~DVS~~ D_{vs} at which the partition to root changes	Masutomi et al. (2016)
~~DVS_{lef1}~~ $D_{\mathrm{vs,lef1}}$	Parameterized	-	1st point of ~~DVS~~ D_{vs} at which the partition to leaf changes	Masutomi et al. (2016)
~~DVS_{lef2}~~ $D_{\mathrm{vs,lef2}}$	Parameterized	-	2nd point of ~~DVS~~ D_{vs} at which the partition to leaf changes	Masutomi et al. (2016)
~~DVS_{pnc1}~~ $D_{\mathrm{vs,pnc1}}$	Parameterized	-	1st point of ~~DVS~~ D_{vs} at which the partition to panicle changes	Masutomi et al. (2016)
~~DVS_{pnc2}~~ $D_{\mathrm{vs,pnc2}}$	Parameterized	-	2nd point of ~~DVS~~ D_{vs} at which the partition to panicle changes	Masutomi et al. (2016)
~~$eDVS$~~ $D_{\mathrm{vs,e}}$	Parameterized	-	~~DVS~~ D_{vs} at emergence	Masutomi et al. (2016)
~~f_d~~ f_{d}	0.015	-	respiration factor	Sellers et al. (1996b)
~~f_{stc}~~ f_{stc}	Parameterized	-	fraction of glucose allocated to starch reserves	Masutomi et al. (2016)
~~$h_{gt,aa}$~~ h_{aa}	Parameterized	-	parameter for relation between leaf area index (LAI) and height before heading	Masutomi et al. (2016)
~~$h_{gt,ab}$~~ h_{ab}	Parameterized	-	parameter for relation between LAI and height before heading	Masutomi et al. (2016)
~~$h_{gt,ba}$~~ h_{ba}	Parameterized	-	parameter for relation between LAI and height after heading	Masutomi et al. (2016)
~~$h_{gt,bb}$~~ h_{bb}	Parameterized	-	parameter for relation between LAI and height after heading	Masutomi et al. (2016)
~~$hDVS$~~ $D_{\mathrm{vs,h}}$	Parameterized	-	~~DVS~~ D_{vs} at heading	Masutomi et al. (2016)
~~k_{yld}~~ k_{yld}	Parameterized	-	ratio of crop yield to dry weight of panicle at maturity	Masutomi et al. (2016)
~~k_{SLW}~~ $k_{S_{\mathrm{lw}}}$	Parameterized	-	parameter for the relation between ~~SLW and DVS~~ S_{lw} and D_{vs}	Masutomi et al. (2016)
m	9	-	the slope of the Ball-Berry model	Sellers et al. (1996b)

continued (Table 6)

Variable	Value	Units	Description	Source
~~$mGDS$~~ $G_{\mathrm{ds,m}}$	Parameterized	K·s	growing degree second at maturity	Masutomi et al. (2016)
~~P_{rot}~~ P_{rot}	Parameterized	-	ratio of glucose partitioned to root	Masutomi et al. (2016)
~~P_{lef}~~ P_{lef}	Parameterized	-	ratio of glucose partitioned to leaf from glucose partitioned to shoot	Masutomi et al. (2016)
~~$r_{d1,lef}$~~ $r_{\mathrm{d1,lef}}$	Parameterized	s^{-1}	ratio of dead leaf at harvest	Masutomi et al. (2016)
~~$r_{rm,stc}$~~ $r_{\mathrm{rm,stc}}$	$1.16*10^{-6}$	s^{-1}	ratio of remobilization	Bouman et al. (2001)
~~r_{rt}~~ r_{rt}	$1.16*10^{-7}$	m s^{-1}	growth ratio of root	Penning de Vries et al. (198
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)
~~SLW_{mx}~~ $S_{\mathrm{lw,mx}}$	Parameterized	kg m^{-2}	maximum specific leaf area	Masutomi et al. (2016)
~~SLW_{mn}~~ $S_{\mathrm{lw,mn}}$	Parameterized	kg m^{-2}	minimum specific leaf area	Masutomi et al. (2016)
s_1	Parameterized	K^{-1}	temperature dependence of ~~$\overline{V}_{max,x}$ on $\overline{V}_{mc,x}$~~ $\overline{V}_{\mathrm{max},x}$ on $\overline{V}_{\mathrm{mc},x}$	Masutomi et al. (2016)
s_2	Parameterized	K	temperature dependence of ~~$\overline{V}_{max,x}$ on $\overline{V}_{mc,x}$~~ $\overline{V}_{\mathrm{max},x}$ on $\overline{V}_{\mathrm{mc},x}$	Masutomi et al. (2016)
s_4	281	K	temperature dependence of ~~$\overline{V}_{max,x}$ on $\overline{V}_{ms,x}$~~ $\overline{V}_{\mathrm{max},x}$ on $\overline{V}_{\mathrm{ms},x}$	Sellers et al. (1996b)
~~T_b~~ T_{b}	281.15	K	minimum temperature for development	Bouman et al. (2001)
~~T_o~~ T_{h}	~~303.15~~313.15	K	~~optimal~~ maximum temperature for development	Bouman et al. (2001)
~~T_h~~ T_{o}	~~313.15~~303.15	K	~~maximum~~ optimal temperature for development	Bouman et al. (2001)
~~$trDVS$~~ $D_{\mathrm{vs,tr}}$	Parameterized	-	~~DVS~~ D_{vs} at transplanting and at which transplanting shock starts	Masutomi et al. (2016)
~~$teDVS$~~ $D_{\mathrm{vs,te}}$	Parameterized	-	~~DVS~~ 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)
~~$V_{max}(0)$~~ $V_{\mathrm{max}}(0)$	Parameterized	μ mol m^{-2} s^{-1}	maximum Rubisco capacity at the canopy top	Masutomi et al. (2016)
~~$z_{rt,mx}$~~ $z_{\mathrm{rt,mx}}$	0.3	m	maximum root depth	Penning de Vries et al. (198
~~β_{ce}~~ β_{ce}	0.98	-	GPP transition factor	Sellers et al. (1996b)
~~ϵ_e~~ ϵ_{e}	0.08	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 ~~CO2~~ CO_2 for photosynthesis down-regulation	Arora et al. (2009)
~~c_{pm}~~ c_{pm}	870	J kg^{-1} K^{-1}	specific heat of soil minerals	Campbell and Norman (199
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~~ d_{f}	$\sec(2\pi(53/360))$	-	scattered factor	Watanabe and Ohtani (1995
F	0.5	-	distribution of leaf orientation	Goudriaan and van Laar (19
~~K_n~~ K_{n}	0.3	-	vertical distribution of nitrogen	Oleson and Lawrence (2013
~~k_{ts0}~~ k_{ts0}	0.25	W m^{-1} K^{-1}	thermal conductivity of dry soil	Campbell and Norman (199
~~k_{tss}~~ k_{tss}	1.58	W m^{-1} K^{-1}	thermal conductivity of saturated soil	Best et al. (2011)
$[O_2]$	20900	Pa	partial pressure of intercellular O_2	Collatz et al. (1991)
~~r_g~~ r_{g}	0.1	-	albedo of surface ~~water~~ for shortwave radiation	Maruyama and Kuwagata (2
s_3	0.2	K^{-1}	temperature dependence of ~~$\overline{V}_{max,x}$ on $\overline{V}_{ms,x}$~~ $\overline{V}_{\mathrm{max},x}$ on $\overline{V}_{\mathrm{ms},x}$	Masutomi et al. (2016)
s_5	1.3	K^{-1}	temperature dependence on ~~$\overline{R}_{d,x}$~~ $\overline{R}_{\mathrm{d},x}$	Sellers et al. (1996b)
s_6	328	K	temperature dependence on ~~$\overline{R}_{d,x}$~~ $\overline{R}_{\mathrm{d},x}$	Sellers et al. (1996b)
~~z_{Ms}~~ z_{Ms}	0.001	m	roughness length of surface ~~water~~ for momentum	Kimura and Kondo (1998)
~~z_{Qs}~~ z_{Qs}	0.001	m	roughness length of surface ~~water~~ for specific humidity	Kimura and Kondo (1998)
~~z_{Ts}~~ z_{Ts}	0.001	m	roughness length of surface ~~water~~ for heat	Kimura and Kondo (1998)
~~β_{pc}~~ β_{pc}	0.95	-	GPP transition factor	Sellers et al. (1996b)
ϵ	0.96	-	longwave emissivity of surface ~~water~~	Campbell and Norman (199
~~γ_d~~ γ_{d}	0.9	-	response parameter to elevated CO_2	Arora et al. (2009)
~~γ_{gd}~~ γ_{gd}	0.42	-	response parameter to elevated CO_2	Arora et al. (2009)
~~τ_b~~ τ_{b}	$8.64*10^{6}$	s	recession constant for base water flow (100day)	Hanasaki et al. (2008)