Application of the Simple Biosphere Model (SiB2) to a Paddy Field for a Period of Growing Season in GAME-Tropics

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Abstract

The simple biosphere model (SiB2) of Sellers et al. and the revised SiB2 (SiB2-Paddy) incorporated with a paddy model are compared and evaluated using micrometeorological data measured in the paddy field that is one of the GAME-Tropics experimental sites in Thailand. In terms of the diurnal cycle, simulated net radiation, and latent heat flux, the two models are in good agreement with the observation, except for the diurnal variation of latent heat flux simulated by SiB2. Sensible and soil heat fluxes, and assimilation rate by SiB2-Paddy agree well with the observation; however, those simulated by SiB2 are found to be biased. Canopy, water, and soil temperature are also well simulated by SiB-Paddy with parameter adjustment. In terms of the total energy and water balance, net radiation, latent heat flux, and assimilation rate do not differ much between the simulations and the observation. This is partly because the values of sensible heat and soil heat fluxes are too small compared to net radiation and latent heat flux, and the mean biases are not significant. However, SiB2-Paddy is required for realistic simulations of the diurnal cycles of latent heat flux and surface temperature.

1. Introduction

Many numerical studies of atmospheric circulation and precipitation were carried out using atmospheric general circulation models (GCMs) incorporated with land surface models (LSMs). Results from GCMs are strongly influenced by their interaction with LSMs, which compute the radiation, momentum, and energy exchanges between the atmosphere and land surface (Garratt 1993; Betts et al. 1996; Pitman et al. 1999). LSMs have become more complicated by inclusion of submodels that consider photosynthesis-conductance, vegetation dynamics, and biogeochemical cycles in order to represent the complex global ecosystem. Using the GCM coupled with the LSM with such submodels makes possible realistic simulation studies of global warming, climate change, and terrestrial net primary production on the global scale (Denning et al. 1996a and b; Foley et al. 1996; Sellers et al. 1996b; Bonan 1998; Cramer and Field 1999). However, because of the problem of unanticipated feedback to GCM from LSM, the thorough performance evaluation of its various subcomponents and their functioning as a complete ensemble is essential to remove a serious error prior to implementing the LSM in the GCM.

Using the simple biosphere model (SiB) of Sellers et al. (1986), which is one of the LSMs, a number of sensitivity studies were carried out to evaluate the performance (Sellers and Dorman 1987; Sellers et al. 1989). The studies revealed not only that SiB is sensitive to many of the morphological parameters, but also that transpiration from tall vegetation is sensitive to those parameters controlling the canopy resistance. Sellers et al. (1992) updated SiB to include a new single-layer canopy integration scheme incorporated with a photosynthesis-conductance scheme (Collatz et al. 1991 and 1992). Later, SiB2 which describes biogeochemical processes controlling the energy, water, and carbon exchanges between terrestrial surface and the atmo-
sphere, was developed (Sellers et al. 1996a and c), and applied to simulation studies of global warming and climate change (Randall et al. 1996; Sellers et al. 1996b; Zhang et al. 1998; Sellers et al. 1997). After SiB was published, due to improvements by a number of evaluation and formulation studies, the outstanding performance of SiB2 was achieved. Nevertheless, improvement and evaluation of SiB2 have been continued for more universal and reliable simulations. For example, Colello et al. (1998) reported that the largest errors were encountered in the simulation of soil respiration by an off-line simulation using SiB2; this was improved by changing the extraction by roots from soil layers and the soil texture specification.

With the Indochina Peninsula as a study area, numerical studies of climatic effects of tropical deforestation using a regional climate model (Kanae et al. 2001), and the LSM impacts of applying to GCM the in situ vegetation types as deforestation result on Thailand (Giambelluca et al. 1996) were explored. Also, in the Chao Phraya river basin of Thailand, the main experimental area of GAME-Tropics (http://hydro.iis.u-tokyo.ac.jp/Game/game-T.html), which is one of the subprojects of GEWEX Asian Monsoon Experiment (GAME), various studies have been carried out. In particular, this area has large paddy field which is 26% in the land use and is equivalent to 62% of the forest area in the country (Arbkbahirama et al. 1988). Paddy field is one of the important land use, not only in those areas, but also in Asia. However, few numerical studies using GCMs and LSMS available to reveal the climatic role of paddy field in those areas, because a suitable LSM with which to properly consider paddy field is lacking. Observation and modeling studies to describe the exchange of micrometeorological components in paddy field (Maitani and Ohtaki 1987; Maitani and Kashiwagi 1992; Aoki et al. 1998), and to predict rice productivity due to climate change (Inoue 1985 and 1987; Horie et al. 1995; Olzyk 1999) have been carried out. However, there are still few studies to develop an LSM describing paddy field for use within GCMs.

Therefore, the aim of this paper are to improve the ability to consider paddy field in SiB2, and to evaluate the revised SiB2 using micrometeorological measurements obtained in a paddy field under the framework of GAME-Tropics. Because a paddy field stores surface water, and the water has an important role in the surface energy and water balance for the rainy season. Also, a paddy field with stored water is the important land use in Asia in terms of area and food production.

2. Model structure of SiB2-Paddy

In this section, the structure and formulation of the paddy model, namely SiB2-Paddy, and only the revised part of the governing equations in the original SiB2 are described. The vegetated surface of SiB2 is composed of a canopy layer, canopy air space, and a soil layer, and has subschemes to calculate the energy balance between both surface layers and canopy air space. Accordingly, each layer absorbs radiation, and the available energy is divided into latent heat flux (\(\Delta T\)), sensible heat flux (\(H\)), heat storage (\(C_s \cdot \Delta T/\Delta t\)), and energy transfers due to phase change (\(\xi\)). However, a full explanation of energy transfers due to phase changes in water or snow-ice stored on the canopy, water or ground (\(\xi_c\), \(\xi_w\) and \(\xi_g\)) were omitted, because the experimental area is located in a tropical region. Figure 1 shows the transfer pathways as conceptualized in SiB2-Paddy. Within the structure of the original SiB2, we added one layer of a water body between the canopy and the soil layer. The model has two hypotheses: First, when the short wave radiation, which is the remainder after absorption by the vegetation canopy, reaches the water surface, it is absorbed completely in the water body, because the water body is very muddy. Second, the temperature change due to the water inflow/outflow is negligible, because it is non-irrigated paddy field. The newly incorporated and revised prognostic variables are water temperature (\(T_w\)) and surface soil temperature (\(T_s\)). New and revised governing equations are:

\[
C_w \frac{\partial T_w}{\partial t} = Rn_w - H_w - \Delta T_w - \lambda \frac{T_w - T_g}{(D_w + D_g)/2},
\]

\[
C_g \frac{\partial T_g}{\partial t} = Rn_g + \lambda \frac{T_w - T_g}{(D_w + D_g)/2} - \frac{2\pi C_d}{\tau} (T_g - T_d).
\]

where

\(T\) temperature (K);

\(Rn\) net radiation (W m\(^{-2}\));

\(H\) sensible heat flux (W m\(^{-2}\));

\(\Delta T\) latent heat flux (W m\(^{-2}\));
Fig. 1. Transfer pathways as conceptualized in SiB2-Paddy. Left side is aerodynamic parameters and right side is energy balance of this model. Bold-under line characters are new incorporated variables. Symbols: $r_1 = \text{aerodynamic resistance between canopy air space and reference height}$, $r_2 = \text{bulk canopy boundary layer resistance}$, $r_3 = \text{aerodynamic resistance between ground and canopy air space}$, $z_2 = \text{canopy top height}$, $z_1 = \text{canopy base height}$, $D = \text{depth}$, $R_n = \text{net radiation}$, $LE = \text{latent heat flux}$, $H = \text{sensible heat flux}$, $W = \text{water heat storage}$, $G = \text{soil heat storage}$. Subscripts: $c = \text{canopy layer}$, $s = \text{surface soil layer (0.02 m)}$, $d = \text{deep soil}$.

\[
C = \text{effective heat capacity (J m}^{-2} \text{K}^{-1});
\]
\[
D = \text{depth (m)};
\]
\[
\lambda = \text{thermal conductivity (W m}^{-1} \text{K}^{-1});
\]
\[
\tau = \text{day length (s)}.
\]

The subscripts $w$, $g$, and $d$ refer to the water body, surface soil, and deep soil in all equations, respectively.

Typical surface energy balance and thermal conductivity between water body and soil surface are considered in equation (1). The equation (2) for $T_g$ is also revised, because surface of energy exchange with canopy air space is water surface instead of soil surface (Fig. 1). Consequently, water heat storage, $W$ (i.e. $C_w \cdot \partial T_w / \partial t$), and surface soil heat storage, $G_g$ (i.e. $C_g \cdot \partial T_g / \partial t$) are simulated using the above two equations. Associated equations for surface energy balance at water body are defined as:

\[
R_{nw} = S_w + L_w + \sigma T_c^4 V \delta t - 2\sigma T_w^4 + \sigma T_g^4,
\]
\[
H_w = \rho c_p \frac{T_w - T_a}{r_3},
\]
\[
LE_w = \frac{\rho c_p}{\gamma} \frac{e_c(T_w) - e_a}{r_3}.
\]

where

- $S$ = downward short wave radiation (W m$^{-2}$);
- $L$ = downward long wave radiation (W m$^{-2}$);
- $V$ = canopy cover fraction (dimensionless);
- $\sigma$ = Stefan-Boltzmann constant (W m$^{-2}$ K$^{-4}$);
$\delta t$ absorption rate of infrared radiation by vegetation (W m$^{-2}$);
$\rho$ density of air (kg m$^{-3}$);
$c_p$ specific heat of air (J kg$^{-1}$ K$^{-1}$);
$\gamma$ psychrometric constant (Pa K$^{-1}$);
$c$ vapor pressure (Pa);
$e_{(T)}^{*}$ saturation vapor pressure at temperature T(Pa);
$r_3$ aerodynamic resistance between ground and canopy air space (s m$^{-1}$).

The subscripts $a$, and $c$ refer respectively to the air and canopy in all equations. Finally, the revised equation for the net radiation at soil surface ($Rn_\beta$) is:

$$Rn_\beta = \sigma T_w^4 - \sigma T_g^4,$$

where only long wave radiation is considered.

3. Experimental site, instrumentation and simulation design

3.1 Experimental site

The experimental station is located on non-irrigated paddy field approximately 15 km west of Sukhothai, in the Chao Praya river basin of Thailand (17°03′N, 99°42′E) at an altitude of 50 m. The micrometeorological data was obtained during the rainy season, from 1 to 6 September 1999. The experimental tower was installed in a uniform paddy field and fetches are extended a number of kilometers in most directions. The climatologically mean rainfall pattern in this area exhibits a remarkable seasonal dependence, with mean monthly maximum value of 230 mm in September and minimum value of 5 mm in January (the means for 1955 through 1994 data from the Thailand Meteorological Department). Over the period of data collection, the mean values of temperature ($T_a$), vapor pressure ($e_a$) and wind speed ($u_a$) above the canopy are 302.8 (±2.0) K, 29.9 (±2.8) hPa, and 1.7 (±1.1) m s$^{-1}$, respectively. The peak of hourly mean values of short wave radiation ($S$) was 914 (±55) W m$^{-2}$, and the minimum and maximum of net radiation ($Rn$) were $-42$ (±4) W m$^{-2}$ at nighttime and 766 (±62) W m$^{-2}$ at daytime. The long wave radiation ($L$) remained comparatively constant in 439 (±18) W m$^{-2}$ for the experimental period compared to that of $S$.

3.2 Instrumentation

Fluxes such as LE, $H$, and $CO_2$ for the validation of SiB2 were measured with EUROFLUX methodology (Aubinet et al. 2000). The system comprises a three axes sonic anemometer (Research HS, Gill) and a closed path infrared gas analyzer (LI-6262, LI-COR). The anemometer was mounted on an iron-scaffolding tower at the reference height, 8 m above the top of vegetation canopy and operated routinely during the period of data collection. The digital signals, such as reference temperature ($T_r$) and wind speed ($u_a$) are sampled at a rate of 10 Hz, which corresponds to the maximum sampling rate for infrared gas analyzer. Six sample measurements at 10 min intervals were integrated into the hourly average values of $S$ and $L$ by CNR1 (Kipp and Zonen), $e_a$ by ventilated wet- and dry- bulb psychrometer, $T_a$ by Pt-100, and canopy ($T_c$), water ($T_w$) and surface soil ($T_s$) temperature by thermocouples. Water temperature was measured at 0.01, 0.07 and 0.15 m depth and hourly rainfall was determined as the integrated counts from a tipping bucket rain gauge.

3.3 Simulation design

Agriculture/C3 grassland and clay-clay loam in the standard SiB2 parameter sets for vegetation and soil were used for the simulation. However, measured values were used for such morphological vegetation parameters as top and base height of canopy ($z_l$ and $z_2$), canopy cover fraction ($V$), green leaf fraction ($N$), and leaf area index ($LAI$). The $V$ was estimated with an imaging software, by detecting the ratio of the green part per unit area on photographs taken over the paddy field. Using a leaf analyzer (AAM-8, Hayashi-Denkou), the leaf areas of green and non-green parts were measured per unit area and the $N$ is estimated by the ratio between values of the two parts. The $LAI$ is measured using a plant canopy analyzer (LAI–2000, LI-COR).

Aerodynamic parameters such as optical depth of the direct beam ($g(\mu)/\mu$), roughness length ($z_0$), zero plane displacement ($d$), canopy source height for heat ($h_c$), resistance coefficients of the bulk boundary layer ($C_1$), and resistance coefficients of ground ($C_2$), were calculated with the aerodynamic submodel in SiB2 using the measured morphological parameters (Sellers et al. 1996a; Table 1). The adjusted value of $C_1$ and $C_2$ were also used for the SiB2-Paddy. The initial values of temperature were based on the observations. The interception stores were assumed to be zero, and the soil moisture contents were initialized with 1.0. The paddy field was inundated throughout the experimental
Table 1. Morphological and aerodynamic parameters used in original SiB2 (O), SiB2-Paddy (P), and adjusted SiB2-Paddy (PA) runs. Parameters were measured directly, and were calculated with aerodynamic sub model in SiB2 using the measured parameters. The values of $C_1$ and $C_2$ in PA were calibrated. Symbols: ND: dimensionless, $-$: same value of left side.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Units</th>
<th>O</th>
<th>P</th>
<th>PA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_2$</td>
<td>Canopy top height</td>
<td>m</td>
<td>0.5</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$z_i$</td>
<td>Canopy base height</td>
<td>m</td>
<td>0.1</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$V$</td>
<td>Canopy cover fraction</td>
<td>ND</td>
<td>0.5</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$g(\mu)/\mu$</td>
<td>Optical depth of the direct beam</td>
<td>ND</td>
<td>0.5</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$N$</td>
<td>Green leaf fraction</td>
<td>ND</td>
<td>0.9</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>LAI</td>
<td>Leaf area index</td>
<td>ND</td>
<td>2</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$z_0$</td>
<td>Roughness length</td>
<td>m</td>
<td>0.05</td>
<td>0.03</td>
<td>$-$</td>
</tr>
<tr>
<td>$d$</td>
<td>Zero plane displacement</td>
<td>m</td>
<td>0.2</td>
<td>0.3</td>
<td>$-$</td>
</tr>
<tr>
<td>$C_i$</td>
<td>Bulk boundary-layer resistance coefficient ($r_b$)</td>
<td>$(s , m^1)^{1/2}$</td>
<td>25</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>$C_2$</td>
<td>Ground to canopy air-space resistance coefficient ($r_d$)</td>
<td>ND</td>
<td>79</td>
<td>263</td>
<td>79</td>
</tr>
<tr>
<td>$h_a$</td>
<td>Canopy source height for heat</td>
<td>m</td>
<td>0.4</td>
<td>$-$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

The hourly mean values of micrometeorological measurements were used for the boundary forcing of the models.

4. Results and discussions

4.1 Diurnal cycle of the surface energy balance

Only the results for the low leaf area condition (LAI=2) is shown here, because Kim et al. (1999a; 1999b) reported that simulated $lE$ and $H$ by SiB2 corresponded well with observations for the high leaf area condition (LAI=4) of a paddy field.

Figure 2 shows the simulated and observed time series of surface energy balance components ($R_{n}$, $lE$, $H$, and $G$), and two prognostic variables ($T_a$ and $T_g$) by the original SiB2 (O) during the experimental period. Water heat storage ($W$) and $T_w$ are not simulated in this model. The simulated $R_{n}$ generally agrees with the observation both in terms of magnitude and diurnal variation (Fig. 2b). However, the other components ($lE$, $H$, and $G$) are not matched with the observation. Especially, large differences between the simulation, and observation of those components, are distinct under fair weather conditions (Fig. 2a and 2b). In detail, the simulated $lE$ is slightly underestimated and exhibits early peak time (Fig. 2a). Contrasting with the underestimated $lE$, the simulated $H$ is overestimated and the difference between the observation and simulation is approximately double under fair weather conditions (Fig. 2a). In the simulation of O, simulated $G$ is equal to the observed $G+W(GW)$ because the water body is not considered within vegetation type of the agriculture/C$_3$ grassland in SiB2. The simulated $G$ is underestimated compared with the observed GW, and the diurnal variations are different (Fig. 2b). Simulated $T_g$ is compared with measured $T_w$, because the soil surface is covered with water. The $T_g$ is overestimated by approximately 10 K in comparison with the observed $T_w$ for daytime. The simulated diurnal variation of $T_g$ is over 20 K, and observed $T_w$ is 7 K. $T_w$ is also overestimated by 5 K under high solar radiation. The simulated diurnal variation of $T_w$ is over 12 K, even though the observation is 5 K. These disagreements seem to be caused by no consideration of the water body. As seen in previous observations, the water body has an important role in the energy balance. The characteristics
Fig. 2. Comparison of simulated and observed time-series for (a) latent heat flux ($\dot{E}$) and sensible heat flux ($H$), (b) net radiation ($R_n$), Water heat flux ($W$) and soil heat flux ($G$), and (c) canopy ($T_c$), water ($T_w$) and soil surface temperature ($T_s$). Abbreviations: Obs = observation, Sim = simulation of SiB2. The experimental period is from 1 (11:00) to 6 (5:00) September 1999.
Fig. 3. Same as figure 2 except for the results by SiB2-Paddy.

of surface temperature in paddy fields which are different from other vegetation types (Tsukamoto 1993; Aoki et al. 1998; Luo and Goudriaan 1999). Therefore, considering the water body for appropriate boundary conditions above the paddy field is necessary. We employed a new model, namely SiB2-Paddy (P), for a realistic simulation and for the solution of the problems above. This P is tested and evaluated by the same methodology of O simulation. Aerodynamic parameters ($z_0$, $d$, $C_1$, and $C_2$) of P are different from O, because the roughness lengths of soil surface and water surface are
different (Table 1). Figure 3a shows the simulated time-series of IE and H with the observation using the new P during the experimental period. Simulated H corresponded with measurements for the diurnal cycle with slight underestimation of simulated IE. Also, simulated time-series of W and G are closely matched with the observation (Fig. 3b). From this result, unrealistic H of the original SiB2 should be due to the unreliable simulation of W and G. Simulation of Tc, Tw, and Tg, are improved compared to the O simulation, but are still overestimated (Fig. 3c). Temperature is one of the important environmental factors for stomata movement, and its movement affects transpiration and photosynthesis. Therefore, the precise simulation of IE and its assimilation rate could be enhanced by a accurate temperature simulation, even though its direct effect on the surface energy balance is not significant. The resistance coefficient of the bulk boundary-layer (C1), and the resistance coefficient of ground to canopy air-space (C2) have important roles in aerodynamic variables for the transport of energy from canopy and soil surface to canopy air space (Sellers and Dorman 1987). Those are proportional to bulk boundary-layer resistance (r2) and ground to canopy air-space resistance (r3), respectively (Fig. 1). Accordingly, using the same method of Ikoma et al. (2000), we calibrated C1 and C2 of P for a more realistic simulation of Tc, Tw, and Tg (Table 1). Figure 4 shows the comparison of Tc, Tw and Tg by adjusted SiB2-Paddy (PA) with the observations. It is apparent that the results by adjusted SiB2-Paddy well matches and components of surface energy balance are reliable as well. However, the simulated Tc and Tw are still underestimated because of the overestimation of IE during nighttime.

4.2 Diurnal cycle of assimilation rate

It is necessary to compare the simulated assimilation rate (A) with the observed CO2 flux (F) because A is used to calculate a consistent canopy resistance (rc) and important role in the simulation of IE (Sellers et al. 1996a) in SiB2. However, the direct comparison of simulated A and observed F is found to be erroneous, because A is only the magnitude of photosynthesis by vegetation except soil respiration and the observed F is the budget of photosynthesis and soil respiration. Fortunately, this problem can be eliminated in this study, because the soil surface is covered with a water body within paddy field. Time-series of three simulated A, by the original SiB2 (O), SiB2-Paddy (P) and adjusted SiB2-Paddy (PA), are shown with observed F using the micrometeorological method (Fig. 5a). Also three predicted canopy resistances (rc), and canopy resistance stress factors, are shown in Figure 5b and 5c, respectively. Simulated A by PA is in accordance with the observed one compared to the other simulations. Canopy resistance stress factor is influenced by three components: temperature, vapor pressure, and the leaf water potential stress factor of canopy (Sellers et al. 1992; Sellers and Dorman 1987). The range of canopy resistance stress factor is from 0 to 1, and the value of 1 means that photosynthesis is not limited by the canopy resistance stress factor. In simulations of O and P, rC was overestimated because underestimating the canopy resistance stress factor, due to the overestimation of Tc (Fig. 2c and Fig. 3c). Accordingly, those simulated assimilation rates are underestimated compared to PA. Denning et al. (1996a) and Colelo et al. (1998) reported that SiB2 simulations with calibration of physiological parameters agree well with observations in terms of photosynthesis, except overestimated H, and slightly underestimated A. Sellers et al. (1989) showed that suitable values of rc, and the canopy resistance stress factor, and appropriate calibration are required for realistic simulations of canopy photosynthesis, evapotranspiration, and aerodynamic parameters. In the case of PA, H, Tc, and Tw were realistically simulated by calibrated C1 and C2. As a result, the corresponding assimilation rate is in good agreement with observation (Fig. 4 and 5a).

4.3 Mean values of surface energy balance and assimilation rate

Figure 6 illustrates the mean surface energy balance components and CO2 exchange from observation, and by three simulations. In figure 6a, the simulated Rn corresponds to observation under 10% of the mean value. Also, results of IE is the same as Rn on the total balance between daytime and nighttime even if simulated IE using original SiB2 (O) is underestimated in nighttime. Evaporation during nighttime was observed, and the simulation by SiB2-Paddy (P) is well captured by this phenomenon (Fig. 2a and Fig. 3a). However simulated mean H using O and P are overestimated and underestimated, respectively. Simulated GW, and W using P, and adjusted SiB2-Paddy (PA) are in good agreement with observation, but simulated GW using O is underestimated. In terms of A,
Adjusted SiB2-Paddy

Fig. 4. Same as figure 2 except for the results by adjusted SiB2-Paddy.

simulation is in accordance with observed $F$ under 10% of the mean values, respectively.

This result shows the averages of the surface energy balance components are not very different between the simulation and the observation, if 10% of the observed mean $R_n$, approximately $\pm 50$ W m$^{-2}$, is applied to mean values of the other components. Because the values of $H$ and $GW$ are too small compared to $R_n$ and $IE$, and the mean biases are not significant. However, the simulated
Fig. 5. Comparison of three simulated and an observed time-series for (a) observed CO₂ flux and simulated assimilation rates, (b) simulated canopy resistances, and (c) simulated stress factor. Abbreviations: Obs = observation, O = simulation of original SiB2, P = simulation of SiB2-Paddy, PA = simulation of adjusted SiB2-Paddy, \( F \) = CO₂ flux, \( A \) = assimilation rate, \( r_c \) = canopy resistance. The experimental period is from September 1 to 6, 1999.

diurnal cycle using O is slightly different from the observation shown above. Beljaars et al. (1995) and Betts et al. (1996) reported that forecasting rainfall has a large sensitivity by the diurnal cycle of surface energy balance. Therefore, realistic simulation of the diurnal cycle should be preferable in addition to the food simulation of mean values and for long-term simulations of GCMs coupled with a LSM, because of interactions between LSM and GCM, and the SiB2-Paddy model is required for
Fig 6. Comparison of the simulated and observed mean values for daytime and nighttime. The daytime mean is the period of more than 0 W m⁻² short wave radiation. (a) Components of surface energy balance. (b) Observed CO₂ flux and simulated assimilation rates. Abbreviations: Obs = observation, O = simulation of original SiB2, P = simulation of SiB2-Paddy, PA = simulation of adjusted SiB2-Paddy. \( Rn \) = net radiation, \( IE \) = latent heat flux, \( H \) = sensible heat flux, \( GW \) = soil and water heat flux, \( G \) = soil heat flux, \( W \) = water soil storage. The experimental period is from 1 to 6 September 1999.
realistic simulations of the diurnal cycles of IE and surface temperatures in the GAME-Tropics.

5. Conclusions

SiB2 was not incorporated with the paddy scheme describing water body and the paddy field in its vegetation types, although the paddy field has a water body which plays an important role in the surface energy balance and is an important ecosystem in GAME-Tropics which is one of the frameworks of GAME. Consequently, we implemented a water layer within the original SiB2, and the revised SiB2, namely SiB2-Paddy, which was evaluated using the meteorological measurements in the paddy field of GAME-Tropics. The result of the original SiB2 simulation shows that net radiation ($R_n$) agrees with the observation, however, simulated latent heat flux (IE) showed early peak, and assimilation rate ($A$), sensible heat flux ($H$), soil heat flux ($G$), surface soil temperature ($T_s$) and canopy temperature ($T_c$) are unrealistic. The SiB-Paddy simulation illustrated that components of surface energy balance, photosynthesis, and prognostic variables are realistic. In terms of total energy and water balance, $R_n$, IE, and $A$ are not very different between the SiB2 and the SiB2-Paddy simulation, and the observation. It is partly because the values of $H$ and $G$ are too small compared to net radiation and IE, and the mean biases are not significant. However, SiB2-Paddy is required for realistic simulations of the diurnal cycles of IE and surface temperature for keeping away the unrealistic LSM simulation, and the realistic temperature simulation is also needed, because it is one of the important environmental factors to plant physiology and the energy balance of paddy field in GAME-Tropics.

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