Research Article

Estimating Rice Panicle Temperature with Three-Layer Model

Yanyan Wang,1 Hiroki Oue,2 Zhijun Luo,1 Ming Chen,3 Shiyu Liu,1 Chunhuo Zhou,1 and Xiaowu He1

1Jiangxi Agricultural University, 1101 Zhimin Road, Economic and Technological Development Zone, Nanchang, 330045 Jiangxi, China
2Faculty of Agriculture, Ehime University, 3-5-7 Tarumi, Matsuyama, Ehime 7908566, Japan
3Hunan University, Lushan Road (S) Yuelu District, Changsha, Hunan 410082, China

Correspondence should be addressed to Hiroki Oue; oue@agr.ehime-u.ac.jp and Zhijun Luo; 106028065@qq.com

Received 11 December 2019; Revised 19 January 2020; Accepted 28 January 2020; Published 20 March 2020

1.Introduction

With increasing concerns about global warming, the impacts of higher temperature on rice production have become a major focus in many rice-producing countries in tropical, subtropical, and temperate regions [1–9]. In China, extreme high temperature in 2003 caused about 5 million tonnes of rice yield loss [10], while unusual temperatures (>40°C) in many areas of Kanto and Tokai regions of Japan resulted in 25% spikelet sterility in 2007 [11].

Rice panicle temperature (T_p) is a key factor for studying high temperature impacts on spikelet sterility. Comparing with measuring T_p by hand, a T_p simulation model could obtain T_p data readily. The two-layer energy budget model which divides the soil layer and canopy layer was widely used to predict rice canopy temperature (T_c), but panicle existed mostly in the upper layer canopy, and we have proved that T_c was different from the upper layer canopy temperature (T_c1), and the upper layer must be separated from the whole canopy for the purpose of estimating T_p. Thus, we developed the three-layer model, contained upper canopy layer with panicle (50–100 cm), lower rice canopy layer (10–40 cm), and water surface layer (≤10 cm) to estimate T_p with general meteorological and vegetation growth data. There were two steps to estimate T_p. The first step was calculating T_c1 and lower layer canopy temperature (T_c2) by solving heat balance equations with canopy resistances. And the second step was estimating T_p with following parameters: (a) the inclination factors of leaves and panicles (F_1, F_2, and F_p) which were decided by fitting the calculated transmissivity of downward solar radiation (TDSR) to the measured TDSR, (b) the aerodynamic resistance between the panicle and atmosphere (r_ap) denoted by wind speed, (c) the panicle resistance for transpiration (r_p) denoted by days after heading, and (d) air temperature and humidity at the panicle’s height (T_ac1 and e_ac1) calculated from the resistances of the pathways of sensible and latent heat fluxes in accordance with Ohm’s law. The model simulated fairly well the T_c1, T_c2, and T_p with root mean square errors (RMSEs) of 0.76°C, 0.75°C, and 0.81°C, respectively, where RMSE of measured T_p and predicted T_p by integrated micrometeorology model for panicle and canopy temperature (IM2PACT) including two-layer model was 1.27°C. This model was validated well by two other rice cultivars, and thus, it demonstrated the three-layer model was a new feasible way to estimate T_p.
strong transpirational cooling by low relative humidity (<20%) brought panicle temperature (T_p) 6.8°C lower than T_a. But spikelet sterility occurred frequently in Jianghan Basin, China, where T_a was not so high, since T_p was 4.0°C higher than T_a under high solar radiation with high RH (>80%) and low wind speed (u < 1 m s⁻¹) conditions [27]. Therefore, T_p instead of T_a is a key factor for high temperature impact study. As measuring T_p was a time-consuming and laborious work, a T_p simulation model was needed to obtain T_p data readily.

Until now, only limited information has been reported about panicle temperature models. Sheehy et al. [28] developed a T_p model with air temperature and thermal burden. Oue et al. [29] measured T_p in every 10 cm rice canopy layer in the CO2 ambient and CO2 elevated plots during the daytime in Wuxi, China, and developed a heat balance model of T_p based on the measured stomatal conductance. To date, the whole canopy temperature (T_c) predicted by the two-layer model has been used to calculate the long-wave radiations to the panicle as shown in the integrated micrometeorology model for panicle and canopy temperature (IM²PACT) [30]. However, panicle exists mostly in the upper layer canopy, and we have proved that T_c is different from the upper layer canopy temperature (T_c1), and the upper layer must be separated from the whole canopy for the purpose of estimating T_p, whereas the multilayer model [31] required many vertical profiles of micrometeorological environments and fluxes of momentum, and heat and vapor within and above a vegetation, making it unusable to predict T_p with insufficient data.

Therefore, the objectives of this paper are (1) to develop a three-layer model to calculate panicle temperature based on general meteorological and vegetation growth data and (2) to compare the performance to estimate T_p by three-layer model and T_p by IM²PACT [30] including two-layer model.

2. Materials and Methods

2.1. Measurements in the Rice Paddy Field. The experimental paddy field was located in the Ehime University Senior High School, Matsuyama, Japan (33°50′N, 132°47′E). The Japonica type rice (cultivar Akitakomachi) was transplanted with 20 × 30 cm spacing on May 27, 2014, and then harvested on September 8, 2014.

The global solar radiation (S_g), downward long-wave radiation (L_d), and upward long-wave radiation (L_u) above the rice canopy were detected using pyranometer CNR-4 (Kipp & Zonen, the Netherlands) at 2.0 m height from the ground. To measure soil heat flux (G), a soil heat plate CHF-HDP01 (Campbell Scientific Inc., Logan, UT, USA) was buried in the soil surface. Air temperature (T_a) and relative humidity (RH) were observed using ventilated psychrometers HMP-45A (Vaisala Inc., Helsinki, Finland), first mounted at 0.6 m and 1.0 m of a 2.5 m tower, and then lifted to 1.0 m and 1.5 m on July 28, respectively, when rice plant was 81 cm in height. Three-cup anemometers 014A (Meteor One, USA) were mounted as the same heights of psychrometers to measure the wind speed (u). Downward and upward long-wave radiations beneath the rice canopy were both measured with PRI-01 (Prede, Japan) sensors. Water surface temperature (T_w) or ground surface temperature (T_g) was measured with the thermocouple sensor. All data were sampled per 10 s; then, they were averaged and recorded per 10 min using a data logger CR23x (Campbell Scientific Inc., Logan, UT, USA).

Three stubs of rice were taken to measure the upper layer canopy temperature (T_c1), the lower layer canopy temperature (T_c2), and the panicle temperature (T_p) per 2 or 3 h in the daytime using an infrared thermometer THL-500 (Tasco, Japan). The solar radiation within rice canopy was measured with a line type pyranometer PCM200 (Prede, Japan) in the center between stubs in parallel and perpendicular directions, of which the average was calibrated from the solar radiation measured with CNR-4 (Kipp & Zonen, the Netherlands) at 2.0 m. The transmissivity of downward solar radiation (TDSR) refers to the ratio of the St in the rice canopy in every 10 cm to that above the rice canopy. Subsequently, the average TDSRs from 50 cm to 100 cm and from 10 cm to 40 cm were set as the upper and lower layer rice canopy TDSRs, respectively. TDSRs were measured from 10 cm to the top of the canopy per 10 cm and 1.2 m (above the rice canopy). The canopy temperature, T_p, and solar radiation within canopy data were recorded using ZR-RX 20 portable multilogger (Omron, Japan). At the heading and the flowering stage, irrigation was performed in the paddy field at 5-day interval. Besides, 8 cm depth irrigation water decreased to 0 through evaporation and infiltration in one and a half days. At the ripening stage, there was almost no water.

Plant area density (PAD) was sampled three rice plants at the interval of one week. The taken three rice plants were cut at intervals of 10 cm, split into components of leaves, stems, and panicles, respectively, and then scanned. Lastly, the area of each part (projected area for panicle) was calculated using ImageJ software. Water depth (d_w) was measured per two or three hours in the daytime. Water surface evaporation (E_s) beneath the rice canopy was measured with the lysimeter (length × width × depth: 60 × 20 × 30 cm) and recorded twice (8:30 and 18:30) per day.

2.2. Estimating Panicle Temperature (T_p) with Three-Layer Model. The input data of the three-layer model to estimate T_p include (a) hourly radiations, (b) temperature, humidity, and wind speed, (c) water surface data, and (d) vegetation growth data. T_p was estimated in two steps. The first step was calculating T_c1 and T_c2 by solving heat balance equations with canopy resistances and the second step was estimating T_p with calculated T_c1 and T_c2.

The schematic of the aerodynamic resistance and upper and lower layer canopy resistances of one-layer and three-layer models is illustrated in Figure 1. The schematic diagram illustrating the method for estimation T_c1, T_c2, and T_p by the three-layer model is shown in Figure 2. And the input parameters required for the calculation in the model are shown in Table 1.
were set as a whole, and energy budget in a paddy field was and atmosphere (W m$^{-2}$), $\text{LET}$ was the latent heat flux for the whole canopy (W m$^{-2}$), $\text{LE}_{p}$ was the latent heat flux on a panicle (W m$^{-2}$), $\text{LE}_{c1}$ was the latent heat flux between upper layer rice canopy and atmosphere (W m$^{-2}$), $\text{LE}_{c2}$ was the latent heat flux between lower layer rice canopy and atmosphere (W m$^{-2}$), $\text{LE}_{g}$ was the latent heat flux between water surface beneath the rice canopy and atmosphere (W m$^{-2}$), $T_{p}$ was the panicle temperature (°C), $T_{c1}$ was the upper layer canopy temperature (°C), $T_{c2}$ was the lower layer canopy temperature (°C), $T_{a}$ was the surface temperature of the paddy field (°C), $e_{at}(T_{a})$ was the saturation-specific humidity at $T_{a}$ (hPa), and $e_{a}$ was the specific humidity of the air (kg kg$^{-1}$).

$T_{p}$ was the surface temperature of the paddy field (°C) calculated based on the upward long-wave radiation ($L_{u}$) and downward long-wave radiation ($L_{d}$), as expressed in the following equation:

$$L_{u} = \varepsilon \sigma T_{a}^{4} + (1 - \varepsilon) L_{d},$$

where $\varepsilon$ was the surface emissivity set as 0.97 in this study.

Based on the data of measured $G$, $\delta W$, $\text{LE}$, and $H$ were calculated by equation (1), and $T_{a}$ was obtained by equation (4). Subsequently, $r_{a}$ was obtained by equation (3b), and lastly $r_{cg}$ was calculated by equation (3c) based on the data of measured $T_{w}$, $e_{w}$, and $\text{LET}$.

In the three-layer model, net radiation ($R_{n}$) sums the net radiation absorbed by upper canopy layer ($R_{uc1}$), the net radiation absorbed by lower canopy layer ($R_{uc2}$), and the net radiation absorbed by water surface layer ($R_{ng}$):

$$R_{n} = R_{uc1} + R_{uc2} + R_{ng}.$$  

The energy budget equations for water surface were written from the following equations:
where $H_g$ was the sensible heat flux between water surface beneath canopy and atmosphere (W m\(^{-2}\)) $LE_g$ was the latent heat flux between water surface beneath canopy and atmosphere (W m\(^{-2}\)) obtained from the water surface evaporation by the lysimeter, $T_g$ was the ground surface temperature (°C) (assumed $T_g=T_w$ in the model), $e_{\text{sat}}(T_g)$ was the saturation-specific humidity at $T_g$ (hPa), $y$ was the psychrometric constant (kPa °C\(^{-1}\)), $r_{ag}$ was calculated by equation (7a) based on the measured $LE_g$ and $T_g$, first, $H_g$ was calculated by equation (7b), and then $R_{ng}$, $R_{nc1}+R_{nc2}$ were calculated by equations (5) and (6), respectively.

The energy budget equations for upper layer canopy (50–100 cm) and lower canopy layer (10–40 cm) were written from equations (8) to (10c):

$$R_{ng} = H_g + LE_g + G + \delta W,$$

$$LE_g = \frac{c_p \gamma \left(e_{\text{sat}}(T_g) - e_a\right)}{\left(r_{ag} + r_g\right)},$$

$$H_g = \frac{c_p (T_g - T_a)}{r_{ag}},$$

$$R_{nc1} + R_{nc2} = H_{c1} + LE_{c1} + H_{c2} + LE_{c2},$$

$$H_{c1} + H_{c2} = H - H_g,$$

$$H_{c1} = \frac{c_p(T_{c1} - T_a)}{r_{ac1}},$$

$R_{nc1}, R_{nc2}$ were calculated by equations (12a)–(13).

**Figure 2**: A schematic diagram illustrating the method for estimating upper and lower layer canopy temperatures ($T_{c1}$ and $T_{c2}$) and panicle temperature ($T_p$). The grey rounded rectangles denote input data, and the grey diamonds denote output data.
Table 1: Input parameters required for the calculation in the three-layer model.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_n$</td>
<td>Net radiation for the whole canopy</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>$G$</td>
<td>Soil heat flux</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>$L_d$</td>
<td>Downward long-wave radiation for the whole canopy</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>$L_u$</td>
<td>Upward long-wave radiation for the whole canopy</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Air temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$e_a$</td>
<td>Water vapor pressure of the air</td>
<td>hPa</td>
</tr>
<tr>
<td>$u$</td>
<td>Wind speed</td>
<td>m s$^{-2}$</td>
</tr>
<tr>
<td>$T_w$</td>
<td>Water temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$d_w$</td>
<td>Water depth</td>
<td>m</td>
</tr>
<tr>
<td>$LE_{a}$</td>
<td>Latent heat flux between water surface beneath canopy and atmosphere</td>
<td>W m$^{-2}$</td>
</tr>
</tbody>
</table>

Forcing parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1$</td>
<td>Green leaf and yellow leaf area index in the upper canopy layer</td>
<td>m$^2$ m$^{-3}$</td>
</tr>
<tr>
<td>$a_2$</td>
<td>Green leaf and yellow leaf area index in the lower canopy layer</td>
<td>m$^2$ m$^{-3}$</td>
</tr>
<tr>
<td>PAR</td>
<td>Photosynthetically active radiation</td>
<td>μ mol m$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>$g_s$</td>
<td>Stomatal resistance</td>
<td>cm s$^{-1}$</td>
</tr>
</tbody>
</table>

Note: $g_s$ was referred to Oue’s literature [32]; other data were observed.

\[
H_{c2} = \frac{c_p\rho(T_{c2} - T_a)}{r_{ac2}}, \quad (9c)
\]

\[
LE_{c1} + LE_{c2} = LE_T - LE_p, \quad (10a)
\]

\[
LE_{c1} = \frac{c_p\rho(e_{sat}(T_{c1}) - e_a)}{\gamma(r_{c1} + r_{ac1})}, \quad (10b)
\]

\[
LE_{c2} = \frac{c_p\rho(e_{sat}(T_{c2}) - e_a)}{\gamma(r_{c2} + r_{ac2})}, \quad (10c)
\]

where $LE_{c1}$ and $LE_{c2}$ were the latent heat flux between upper and lower layer canopy and atmosphere (W m$^{-2}$), respectively. $H_{c1}$ and $H_{c2}$ were the sensible heat flux between upper and lower layer canopy and atmosphere (W m$^{-2}$), respectively. $T_{c1}$ was the upper layer canopy temperature (°C), $T_{c2}$ was the lower layer canopy temperature (°C), $e_{sat}(T_{c1})$ and $e_{sat}(T_{c2})$ were the saturation-specific humidity at $T_{c1}$ and $T_{c2}$ (hPa), $r_{ac1}$ and $r_{ac2}$ were aerodynamic resistances to the transfer of sensible heat between upper and lower layer canopy and atmosphere (s m$^{-1}$), respectively, $r_{c1}$ and $r_{c2}$ were the upper and lower layer canopy resistances (s m$^{-1}$), respectively.

For the aerodynamic resistances, the association of $r_a$, $r_{ag}$, $r_{ac1}$, and $r_{ac2}$ was expressed in the following equation:

\[
\frac{1}{r_a} = \frac{1}{r_{ag}} + \frac{1}{r_{ac1}} + \frac{1}{r_{ac2}}. \quad (11)
\]

In this study, $r_{c1}$ and $r_{c2}$ were calculated by stomatal resistance ($g_s$), green leaf and yellow leaf area index in the upper rice canopy layer ($a_1$), and green leaf and yellow leaf area index in the lower rice canopy layer ($a_2$), as expressed in equations (12a) and (12b). Because $g_s$ was not measured in the experimental paddy field in 2014, $g_s$ developed by Oue [32] was adopted (values as shown in Table 2), as expressed in equation (13):

\[
r_{c1} = \left(\frac{1}{g_s a_1}\right), \quad (12a)
\]

\[
r_{c2} = \left(\frac{1}{g_s a_2}\right), \quad (12b)
\]

\[
g_s = \left[\frac{m_1 PAR + (g_{smax} - g_{smin})}{2n_s}\right] + g_{smin} - \frac{1}{2n_s \times \left[\frac{m_1 PAR + (g_{smax} - g_{smin})}{2n_s}\right]^2 - 4m_1 PAR(g_{smax} - g_{smin})n_s^2}^{1/2}, \quad (13)
\]

where $g_s$ was the stomatal conductance (cm s$^{-1}$), $m_1$ and $n_s$ were parameters, PAR was photosynthetically active radiation (μ mol m$^{-2}$ s$^{-1}$), $g_{smax}$ was the maximum of stomatal conductance (cm s$^{-1}$), and $g_{smin}$ was the minimum of stomatal conductance (cm s$^{-1}$).

With the calculated $r_{c1}$ and $r_{c2}$, $T_{c1}$, $T_{c2}$, $r_{ac1}$, and $r_{ac2}$ were calculated by equations (8)–(10c).

The net radiation input to a panicle ($R_{ns}$)sums shortwave and long-wave radiation absorbed by the panicle (W m$^{-2}$), as expressed in equation (14a). $L_d$ and $L_u$ were long-wave
radiations from a leaf surface adjacent to the panicle and from the atmosphere (W m\(^{-2}\)), respectively. \(S_d\) and \(S_f\) were downward direct and diffused shortwave radiations (W m\(^{-2}\)), respectively, and \(\theta\) was the solar zenith angle (°). \(F_p\) was the inclination factor of panicle, and \(d_f\) was the diffusivity factor for radiation. Besides, the heat balance in the panicle layer was written as equation (14b).

\[
R_{in} = (1 - 0.35)F_p (\sec \theta S_d + 2d_f S_f) + F_p d_f (L_1 + L_a),
\]

\[
R_{in} = 2F_p d_f \sigma T_p^4 + H_p + LE_p,
\]

\[
L_1 = \sigma T_{c1}^4 + (L_d - \sigma T_{c1}^4) \exp(-F_1a_1d_f),
\]

\[
L_a = \sigma T_{c2}^4 + (\sigma T_{c2}^4 - \sigma T_{c1}^4) \exp(-F_2a_2d_f) + \sigma T_{c1}^4 + (\sigma T_{c1}^4 - \sigma T_{c1}^4) \exp(-F_1a_1d_f),
\]

where \(F_1\) and \(F_2\) were the inclination factors of upper and lower layer rice canopy, respectively. \(F_1, F_2,\) and \(F_p\) were decided by fitting the calculated transmissivity of downward solar radiation (TDSR) to the measured TDSR (Figure 3).

Besides, \(H_p\) and \(LE_p\) were sensible and latent heat fluxes on a panicle (W m\(^{-2}\)), which were written as follows:

\[
H_p = \frac{c_p \left[ \frac{T_p - T_{ac1}}{r_{ap}} \right]}{r_{ap}},
\]

\[
LE_p = \frac{c_p \left[ \frac{e_{sat}(T_p) - e(T_{ac1})}{\gamma (r_{ap} + r_p)} \right]}{r_{ap} + r_p},
\]

\[
\left( \frac{T_{c1} - T_{ac1}}{r_{c1}} \right) = \left( \frac{T_{ac1} - T_a}{r_{ac1}} \right),
\]

Moreover, \(T_{ac1}\) was the air temperature at panicle’s height (°C) which was calculated by the transposition of equation (17) as shown in equation (18a), and likewise, \(e_{ac1}\) was the absolute humidity at panicle’s height (hPa) calculated as expressed in equation (18b):

\[
T_{ac1} = \frac{\left( r_{ac1}T_{c1} + r_{c1}T_a \right)}{\left( r_{c1} + r_{ac1} \right)},
\]

\[
e_{ac1} = \frac{\left( r_{ac1}e_{c1} + r_{c1}e_a \right)}{\left( r_{c1} + r_{ac1} \right)},
\]

where \(r_{ap}\) the aerodynamic resistance to the transfer of sensible heat between panicle and atmosphere (s m\(^{-1}\)), denoted the parameter of wind speed (Section 3.3.2), and then \(r_p\) panicle transpiration resistance (s m\(^{-1}\)), denoted the parameter of days after the heading stage (Section 3.3.3). Lastly, \(T_c\) was calculated by combining equations from equations (14a) to (18b).

The average value of measured panicle temperature from 50 cm to 100 cm was set as the measured \(T_p\) which was compared with the \(T_p\) using the three-layer model and by IM2PACT [30] including the two-layer model.

2.3. Statistical Analysis of Models. The measured and calculated \(T_{c1}, T_{c2}\), and \(T_p\) were compared by using error analysis and linear regression. Root mean squared error (RMSE), mean absolute error (MAE), and the standard deviation (SD) [33–35] were adopted to evaluate measured and calculated \(T_{c1}, T_{c2}, T_c\), and \(T_p\) by the models.

2.4. Three-Layer Model Validation. We planted rice (cultivar Hinohikari) from June 21 to November 20, 2015, and rice (cultivar Nikomaru) from June 21 to November 27, 2015, in the same paddy field. PAD of two cultivars was both

---

### Table 2: \(m_i\) and \(g_{i\text{max}}\) in the \(g_i\) model.

<table>
<thead>
<tr>
<th>Date</th>
<th>Canopy layer</th>
<th>VPD (hPa)</th>
<th>(m_i) (cm s(^{-1})) ((\mu) mol m(^{-2}) s(^{-1}))</th>
<th>(g_{i\text{max}}) (cm s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 6</td>
<td>Upper</td>
<td>~18</td>
<td>0.00247</td>
<td>1.500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18~</td>
<td>0.00170</td>
<td>0.500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~10</td>
<td>0.002405</td>
<td>1.500</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>10~15</td>
<td>0.002095</td>
<td>1.200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15~</td>
<td>0.001925</td>
<td>0.800</td>
</tr>
<tr>
<td>August 13</td>
<td>Upper</td>
<td>~8</td>
<td>0.00780</td>
<td>0.820</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8~</td>
<td>0.01246</td>
<td>0.410</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>~8</td>
<td>0.009935</td>
<td>0.515</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8~</td>
<td>0.00833</td>
<td>0.470</td>
</tr>
<tr>
<td>August 27</td>
<td>Upper</td>
<td>~9</td>
<td>0.00282</td>
<td>0.500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9~</td>
<td>0.00195</td>
<td>0.400</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>10~11</td>
<td>0.00261</td>
<td>0.750</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11~</td>
<td>0.00213</td>
<td>0.450</td>
</tr>
<tr>
<td>September 4</td>
<td>Upper</td>
<td>~16</td>
<td>0.003475</td>
<td>0.550</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16~</td>
<td>0.000445</td>
<td>0.400</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>~15</td>
<td>0.001315</td>
<td>0.400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15~16</td>
<td>0.00123</td>
<td>0.400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~16</td>
<td>0.00615</td>
<td>0.400</td>
</tr>
</tbody>
</table>

Note: VPD is vapor pressure deficit, \(g_i\) is the stomatal conductance (cm s\(^{-1}\)), \(g_{i\text{max}}\) is the maximum stomatal conductance (cm s\(^{-1}\)). \(m_i\) and \(n_i\) are parameters.
measured from July 9 to October 14, 2015. Other meteorological instruments were set as same as 2014. Six images were taken to get Tc and Tp by infrared thermometer FLIR-i5 (FLIR systems, USA) at different heights every two or three hours during daytime.

3. Results and Discussion

3.1. General Meteorological Conditions. From July 18 to September 8, the daily average global solar radiation (Sg) was 262 W m⁻², the average air temperature (Ta) was 25 °C, while the highest Ta was 35 °C on July 26, 2014. The average relative humidity (RH) was 81%, and the average wind speed (u) at 1.0 m reached 0.5 m s⁻¹. The total precipitation, the total evapotranspiration, and the daily evapotranspiration were 670 mm, 567 mm, and 5 mm, respectively.

3.2. Plant Area Density (PAD). Panicles’ height ranges from 50 cm to 100 cm, and this part of the rice plant was set as the upper canopy layer. There was no panicle on July 18, and the heading was observed on July 25 (Figure 4). The average of the measured green leaf and yellow leaf area index in the upper layer rice canopy (a₁) ranged from 50 cm to 100 cm, which reached its peak on August 8 (2.5) and then decreased. However, green leaf and yellow leaf area index in the lower layer rice canopy (a₂) decreased from 3 on July 25 to 1.5 on August 8, 2014.

3.3. Modeling Parameter Results

3.3.1. Parameters F₁, F₂, and Fₚ. From August 5 to September 7 in the ripening stage, there was a little diurnal variation of rice morphology.

F₁ was smaller than F₂ because the transmissivity of solar radiation was larger in the upper layer, and the leaf area index of the upper layer canopy (a₁) was also bigger than that in the lower layer (a₂). For example, a₁ was 2.5 and a₂ was 1.5 on August 8. F₁ and F₂ were larger in the morning and afternoon than those at noon, respectively. This was because of the different solar radiation altitudes: in the morning and afternoon, the solar altitude was low, and the solar radiation in the upper layer was large after cutting off, and at noon, the solar radiation was the highest, and the

Figure 3: Vertical profiles of transmissivity of downward solar radiation (TDSR) within the rice canopy in every 10 cm in the paddy field on August 7, 2014 (a–e). (a) 8:50, (b) 10:50, (c) 12:40, (d) 14:50, and (e) 16:40.
solar radiation in the upper layer was smaller after cutting off. This was dependent on the morphology of canopy: leaves stood upright from 60 cm to 100 cm in the upper layer. In the lower layer, in the morning and afternoon, the solar radiation coming diagonally would be cut off by leaves, while at noon, the solar radiation coming from overhead would not be largely cut off, thereby leading to the smaller $F_1$ and $F_2$ during this period. $F_p$ was important after the ripening stage, when the panicles hung their heads and cover the top of the canopy [36]. $F_p$ variation was similar to that of $F_1$ from morning to afternoon because of the similar form of panicles and leaves.

$F_1$ and $F_2$ were smaller than the leaf inclination factor ($F$) in the ripening stage published by Maruyama et al. [37]. To estimate the radiation exchange processes in the rice canopy, the hourly variation of $F_1$, $F_2$, and $F_p$ should be considered for accuracy.

### 3.3.2. Aerodynamic Resistance between the Panicle and Atmosphere ($r_{ap}$)

Table 3 lists the aerodynamic resistance between the panicle and atmosphere ($r_{ap}$) and meteorological data when $r_p$ was set as 0: there was rain before, or dew was found in the morning (August 5, 7, 18, 26, and 28).

As a result of correlation analysis between the meteorological conditions ($S$, $T_a$, RH, and $u$) and $r_{ap}$, it was found that $r_{ap}$ was primarily affected by $u$ with the correlation coefficient of $-0.93$. This is consistent with the results reported by Yan and Oue [38], which suggested that $u$ at 2.0 m from the ground was the major factor affecting $r_w$, $r_{agr}$, and $r_{ac}$ (aerodynamic resistance between the rice canopy and atmosphere). The association between $u$ (0.35 m s$^{-1} < u < 1.75$ m s$^{-1}$) and $r_{ap}$ on the same days is shown in Figure 5(a), as expressed below:

$$ r_{ap} = \frac{6.7551}{u} \quad (19) $$

The friction of the panicle-atmosphere surface could be weakened by the wind speed, and the transport of heat and water vapor between panicle and atmosphere was primarily attributed to molecular diffusion.

Since from August 5 to September 7, the plant height and PAD only had little difference, and the effect of the canopy structure was not considered for $r_{ap}$ in this study.

**Figure 4**: Observed vertical profiles of plant area density (PAD) in the rice paddy field from July 18 to August 15, 2014. (a) July 18, (b) July 25, (c) August 1, (d) August 8, and (e) August 15.
3.3.3. Panicle Resistance for Transpiration ($r_p$). Based on the measured average $T_p$ from 50 cm to 100 cm and $r_{ap}$ calculated by Eq. (19), $r_p$ can be calculated by equations (16a) and (16b). Five days under large $S_o$, high $T_a$ and low RH conditions meaning strong transpiration (August 12, 18, 19, and 31 and September 2) were selected to analyze the influence of $r_p$ (Table 4).

Correlations between days after heading (DAH), meteorological conditions ($S_o$, $T_{ac} = T_a$, $u$, and RH), and $r_p$ suggest that DAH was the major influencing factor, with the correlation coefficient of 0.92. Besides, the changes of $r_p$ against the DAH in the rice paddy field are shown in Figure 5(b). $r_p$ increased asymptotically with the rise in DAH, and their relationship was expressed as follows:

$$r_p = 1.295 \exp (0.0652 \text{DAH}).$$

Thus far, though there was rare information about $r_p$, few researchers have measured the transpirational conductance $g_p$ (=1/$r_p$) in rice paddy fields. Our results showed a similar variation but smaller values compared with those of cultivar "Wuxiangjing 9" reported by Oue et al. [29], in which $g_p$ decreased with the increase in DAH from 0 to 9 under both ambient CO$_2$ and free air CO$_2$ enrichment condition.

This new useful method was presented in this study to denote $r_p$ as a parameter by DAH, while some other methods were reported. In the integrated micrometeorology model for panicle and canopy temperature (IM$^2$PACT) developed by Yoshimoto et al. [30], $g_p$ denotes the parameter of the relative humidity in the vicinity of panicle ($RH_{ac}$), which was not easily and accurately measured with the ordinary ventilated psychrometers. Based on the measurements of rice varieties at the time of flowering, Fukuoka et al. [39] presented three regression equations of $g_p$ as a function of vapor pressure deficit (VPD).

3.4. Modeling $T_p$. The differences between $T_{c1}$ and $T_{c2}$ were presented by Wang et al. [40]. The average values of measured canopy temperature from 50 cm to 100 cm and from 10 cm to 40 cm were set as the measured $T_{c1}$ and $T_{c2}$, which were then compared with the modelled ones, as shown in Figures 6(a) and 6(b). The root mean square errors (RMSE) of modelled $T_{c1}$ and $T_{c2}$ were 0.76°C and 0.75°C. Besides, the difference between modelled and measured $T_{c1}$ and $T_{c2}$ ranged from −1.69°C to 1.35°C and from −1.50°C to 1.61°C, respectively. According to results of the 2-tailed $t$-test statistical analysis, the modelled $T_{c1}$ and $T_{c2}$ values were not significantly different from the measured values at the 0.05 probability level.

In this study, we set $T_c = (T_{c1} \times a_1 + T_{c2} \times a_2)/(a_1 + a_2)$, and measured $T_c$ was compared with that estimated by the two-layer model developed by Yan and Oue [38], as

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>$T_p$ (°C)</th>
<th>$T_{ac}$ (°C)</th>
<th>$u$ (m s$^{-1}$)</th>
<th>$r_{ap}$ (s m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 5</td>
<td>8:30</td>
<td>26.8</td>
<td>27.8</td>
<td>0.4</td>
<td>18.1</td>
</tr>
<tr>
<td>August 7</td>
<td>8:30</td>
<td>26.8</td>
<td>28.4</td>
<td>0.6</td>
<td>10.9</td>
</tr>
<tr>
<td>August 18</td>
<td>8:30</td>
<td>26.3</td>
<td>26.9</td>
<td>0.6</td>
<td>10.9</td>
</tr>
<tr>
<td>August 26</td>
<td>9:30</td>
<td>26.1</td>
<td>27.6</td>
<td>1.7</td>
<td>6.2</td>
</tr>
<tr>
<td>August 28</td>
<td>8:30</td>
<td>24.7</td>
<td>25.1</td>
<td>0.6</td>
<td>12.4</td>
</tr>
</tbody>
</table>

Note: $r_{ap}$ is the aerodynamic resistance to the transfer of sensible heat between panicle and atmosphere, $T_p$ is the panicle temperature, $T_{ac}$ is the air temperature at the panicle’s height, and $u$ is the wind speed.
shown in Figure 7(a). RMSE of \( T_c \) by our three-layer model was 0.63°C, smaller than that by the two-layer model (1.21°C).

As shown in Figure 7(b), RMSE of \( T_p \) estimated by the three-layer model was 0.81°C, smaller than that estimated by IM\(^2\)PACT (1.27°C) including the two-layer model. Better
Table 5: \( T_p \) estimated by three-layer model and by IM\(^2\)PACT [30].

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>( S_r ) (W m(^{-2}))</th>
<th>RH (%)</th>
<th>( T_c ) (°C)</th>
<th>( T_{c1} ) (°C)</th>
<th>( T_{c2} ) (°C)</th>
<th>( T_p ) by IM(^2)PACT (°C)</th>
<th>( T_p ) by three-layer model (°C)</th>
<th>Mea ( T_p ) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 5</td>
<td>9:00</td>
<td>212</td>
<td>28</td>
<td>80</td>
<td>26.7</td>
<td>26.2</td>
<td>28.9</td>
<td>26.6</td>
<td>26.8</td>
</tr>
<tr>
<td>August 5</td>
<td>14:00</td>
<td>201</td>
<td>30</td>
<td>71</td>
<td>28.1</td>
<td>26.9</td>
<td>27.6</td>
<td>26.9</td>
<td>27.0</td>
</tr>
<tr>
<td>August 11</td>
<td>11:00</td>
<td>671</td>
<td>27</td>
<td>73</td>
<td>28.9</td>
<td>25.5</td>
<td>27.0</td>
<td>25.2</td>
<td>25.7</td>
</tr>
<tr>
<td>August 18</td>
<td>9:00</td>
<td>235</td>
<td>27</td>
<td>84</td>
<td>26.3</td>
<td>25.8</td>
<td>26.7</td>
<td>26.2</td>
<td>26.3</td>
</tr>
<tr>
<td>August 18</td>
<td>12:00</td>
<td>599</td>
<td>31</td>
<td>68</td>
<td>26.8</td>
<td>29.5</td>
<td>27.4</td>
<td>28.4</td>
<td>28.4</td>
</tr>
<tr>
<td>August 18</td>
<td>15:00</td>
<td>485</td>
<td>32</td>
<td>68</td>
<td>28.5</td>
<td>26.7</td>
<td>29.7</td>
<td>28.8</td>
<td>28.7</td>
</tr>
<tr>
<td>August 19</td>
<td>9:00</td>
<td>477</td>
<td>32</td>
<td>66</td>
<td>28.2</td>
<td>26.1</td>
<td>29.8</td>
<td>28.5</td>
<td>28.9</td>
</tr>
<tr>
<td>August 19</td>
<td>14:00</td>
<td>745</td>
<td>32</td>
<td>66</td>
<td>28.5</td>
<td>30.5</td>
<td>28.6</td>
<td>29.6</td>
<td>30.1</td>
</tr>
<tr>
<td>August 19</td>
<td>16:00</td>
<td>541</td>
<td>33</td>
<td>59</td>
<td>28.5</td>
<td>28.9</td>
<td>28.5</td>
<td>29.3</td>
<td>29.1</td>
</tr>
<tr>
<td>August 20</td>
<td>17:00</td>
<td>188</td>
<td>29</td>
<td>77</td>
<td>28.3</td>
<td>26.4</td>
<td>28.9</td>
<td>27.8</td>
<td>27.7</td>
</tr>
<tr>
<td>August 20</td>
<td>18:00</td>
<td>80</td>
<td>29</td>
<td>78</td>
<td>27.7</td>
<td>25.1</td>
<td>27.2</td>
<td>26.5</td>
<td>26.6</td>
</tr>
<tr>
<td>August 26</td>
<td>12:00</td>
<td>474</td>
<td>29</td>
<td>67</td>
<td>27.6</td>
<td>26.5</td>
<td>25.7</td>
<td>27.4</td>
<td>27.0</td>
</tr>
<tr>
<td>August 26</td>
<td>15:00</td>
<td>442</td>
<td>30</td>
<td>69</td>
<td>28.2</td>
<td>26.4</td>
<td>30.3</td>
<td>27.5</td>
<td>28.1</td>
</tr>
<tr>
<td>September 3</td>
<td>15:00</td>
<td>86</td>
<td>29</td>
<td>70</td>
<td>27.2</td>
<td>25.2</td>
<td>29.1</td>
<td>26.5</td>
<td>27.1</td>
</tr>
<tr>
<td>September 6</td>
<td>10:00</td>
<td>474</td>
<td>29</td>
<td>71</td>
<td>26.7</td>
<td>24.9</td>
<td>28.1</td>
<td>25.7</td>
<td>26.7</td>
</tr>
<tr>
<td>September 6</td>
<td>16:00</td>
<td>93</td>
<td>28</td>
<td>76</td>
<td>29.3</td>
<td>28.8</td>
<td>27.8</td>
<td>30.1</td>
<td>29.3</td>
</tr>
</tbody>
</table>

Note: Mea means measured.

Table 6: Error analysis statistics of the comparison between measured and calculated canopy and panicle temperatures by models.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>RMSE (°C)</th>
<th>MAE (°C)</th>
<th>SD (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_c ) estimated by three-layer model</td>
<td>0.73</td>
<td>0.81</td>
<td>0.64</td>
</tr>
<tr>
<td>( T_c ) estimated by two-layer model</td>
<td>1.21</td>
<td>1.56</td>
<td>1.25</td>
</tr>
<tr>
<td>( T_{c1} ) estimated by three-layer model</td>
<td>0.76</td>
<td>0.75</td>
<td>0.74</td>
</tr>
<tr>
<td>( T_{c2} ) estimated by three-layer model</td>
<td>0.75</td>
<td>0.63</td>
<td>0.98</td>
</tr>
<tr>
<td>( T_p ) estimated by three-layer model</td>
<td>0.81</td>
<td>0.7</td>
<td>0.67</td>
</tr>
<tr>
<td>( T_p ) estimated by IM(^2)PACT</td>
<td>1.27</td>
<td>0.95</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Note: \( T_c \) is the canopy temperature (°C); two-layer model is developed by Yan and Oue [38]; \( T_{c1} \) and \( T_{c2} \) are the upper and lower layer canopy temperatures, respectively; \( T_p \) is the panicle temperature (°C); IM\(^2\)PACT is integrated micrometeorology model for panicle and canopy temperature developed by Yoshimoto et al. [30]; RMSE is the root mean square error, MAE is the mean absolute error, and SD is the standard deviation.

agreements between the measured and modelled \( T_p \) by the three-layer model than that by IM\(^2\)PACT were obtained, particularly under high \( T_c \) conditions as shown in Table 5. This was because (1) \( T_{c1} \) instead of \( T_c \) was used to predict \( T_p \), since modelled \( T_{c1} \) could be 3°C different with modelled \( T_c \); (2) \( F_1 \), \( F_2 \), and \( F_p \) were determined by fitting the calculated TDSR to the measured TDSR, \( F_1 \), \( F_2 \), and \( F_p \) varied with time because of the different solar radiation altitudes: rather than set to be constant; and (3) \( r_p \) denotes the parameter of measured \( T_p \) by DAH which considering transpiration cooling instead of the RH\(_{ac}\).

RMSE of \( T_p \) estimated by the three-layer model for rice (cultivar Hinohikari) was 0.93°C, and RMSE of \( T_p \) estimated by the three-layer model for rice (cultivar Hinohikari) was 0.89°C. Error analysis statistics of the comparison between measured and calculated canopy and panicle temperatures by models is shown in Table 6.

4. Conclusions

Rice panicle temperature (\( T_p \)) is a key factor for studying high temperature impacts on spikelet sterility. Comparing with measuring \( T_p \) by hand, a \( T_p \) simulation model could obtain \( T_p \) data readily. We developed the three-layer model to estimate \( T_p \) and compared the performance to estimate \( T_c \) by three-layer model and \( T_c \) by two-layer model developed by Yan and Oue [38]; and to compare the performance to estimate \( T_p \) by three-layer model and \( T_p \) by IM\(^2\)PACT [30]. RMSE of \( T_c \) by our three-layer model was 0.63°C, smaller than that by the two-layer model (1.21°C). RMSE of \( T_p \) estimated by the three-layer model was 0.81°C, smaller than that estimated by IM\(^2\)PACT (1.27°C).

However, from July 9 to September 8, 2014, there was 29 rainy days, on which \( T_{c1} \), \( T_{c2} \), and \( T_p \) measurement could not be performed, thereby leading to the reduction of measured data. The highest \( T_p \) was 34.64°C on July 26, 2014, and \( T_{c1} \) and \( T_p \) higher than 35.0°C could not be observed, so our model was not used for extreme temperature. Furthermore, the three-layer model simulated fairly well the \( T_{c1} \), \( T_{c2} \), and \( T_p \) with root mean square errors of 0.76°C, 0.75°C, and 0.81°C, and it was validated well by two other rice cultivars, and thus, it demonstrated that the three-layer model was a new feasible way to estimate \( T_p \). In the future, we will measure stomatal resistance (\( g_s \)) in the rice paddy field and analyze the microclimate observational results in the elevated carbon dioxide concentration experiments [41] with different land use [42] to predict \( T_p \).

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.
Disclosure

Hiroki Oue and Zhijun Luo are the co-first authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was financed in part by the fund “Excellent Engineer” Training Program of General Undergraduate Colleges and Universities in Jiangxi Province: Education and Training Program for Outstanding Engineers in Agricultural Water Conservancy Engineering (Project no. 201442). The authors would like to express their gratitude to Dr. Sanz Griffrino Limin, Ms. Sartika Laban, and Ms. Lian LIU belonging to the hydrometeorology for Environment Engineering Laboratory in Ehime University for their great help in the measurements in the paddy fields. They also thank Mr. Makoto Tanaka and Mr. Kouji Mitsumune from Ehime University Senior High School for supporting our experiments in the paddy fields.

References


