Research Article

Estimating Rice Panicle Temperature with Three-Layer Model

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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 used a two-layer energy budget model which divides the soil layer and canopy layer 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 ($\leq$ 10 cm) to estimate $T_p$ with general meteorological and vegetation growth data. We used 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 ($T_{a1}$ and $e_{a1}$) 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 (IM$^2$PACT) 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 $T_p$.

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 is most sensitive to high temperature during the flowering stage [12–16]. It has been proved that high temperature prevents anther dehiscence and decreases basal pore length of the anther, resulting in low numbers of germinating pollen grains on the stigma, and thus, it causes spikelet sterility [7, 12, 15, 17–22].

Effect of high temperature on spikelet sterility has been studied under different conditions. Matsui et al. [23] reported that spikelet fertility was significantly damaged when daily maximum air temperature exceeded 35°C. Abeywisewardena et al. [24] revealed high temperature condition (35°C day/30°C night) induced complete grain sterility when relative humidity (RH) was 85–95%. Contrary to the results above, [25, 26] demonstrated spikelet sterility of rice did not occur seriously even daily maximum $T_a$ was over 40°C in Australia during the 2004–2006 growing seasons because the
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 CO$_2$ ambient and CO$_2$ 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 (IM$^2$PACT) [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 IM$^2$PACT [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 ($L_{d1}$), and upward long-wave radiation ($L_{u1}$) 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 (Met-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 ($T_{c2}$), the lower layer canopy temperature ($T_{c1}$), and the panicle temperature ($T_p$) per 2 or 3 h in the daytime using an infrared thermometer THI-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 $S$ 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 expressed as follows:

\[ R_n = LET + H + G + \delta W, \]  

\[ \delta W = \frac{C_w d_w [T_{w(t+1)} - T_{w(t)}]}{\delta t}, \]  

where \( R_n \) was the net radiation (W m\(^{-2}\)), \( LET \) was the latent heat flux (W m\(^{-2}\)), \( H \) was the sensible heat flux (W m\(^{-2}\)) for the whole canopy, and \( \delta W \) was the change of storage energy in the water surface (W m\(^{-2}\)) calculated by equation (2) based on the measured water temperatures and water depth. \( LET \) was calculated by the Bowen ratio method (equation 3(a)) with air temperatures and water vapor pressure of air at two different heights, and \( H \) was calculated by equation (1).

Aerodynamic resistance between the whole rice canopy and water surface \( (r_a) \) and the total canopy resistance that consists of rice canopy resistance and water surface resistance \( (r_{cg}) \) was calculated by equations (3b) and (3c):

\[ LET = \frac{(R_n - G)}{(1 + Bo)} \]  

\[ H = \frac{c_p \rho (T_s - T_a)}{r_a} \]  

\[ LET = \frac{c_p \rho [e_{sat}(T_s) - e_a]}{[\gamma (r_a + r_{cg})]} \]  

where \( c_p \) was the specific heat capacity of the air at constant pressure (J g\(^{-1}\) °C\(^{-1}\)), \( \rho \) was the air density (kg m\(^{-3}\)), \( T_s \) was the surface temperature of the paddy field (°C), \( e_{sat}(T) \) was the saturation-specific humidity at \( T \) (hPa), and \( e_a \) was the specific humidity of the air (kg kg\(^{-1}\)).

\( T_s \) 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:

\[ L_u = \varepsilon_s \sigma T_s^4 + (1 - \varepsilon_s) L_d, \]  

where \( \varepsilon_s \) was the surface emissivity set as 0.97 in this study.

Based on the data of measured \( G, \delta W, LE, \) and \( H \) were calculated by equation (1), and \( T_s \) 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 \( T_m, e_m, \) and \( LET \).

In the three-layer model, net radiation \( (R_n) \) sums the net radiation absorbed by upper canopy layer \( (R_{nc1}) \), the net radiation absorbed by lower canopy layer \( (R_{nc2}) \), and the net radiation absorbed by water surface layer \( (R_{nw}) \):

\[ R_n = R_{nc1} + R_{nc2} + R_{nw}. \]  

The energy budget equations for water surface were written from the following equations:

![Figure 1: A schematic representation of the aerodynamic resistance and upper and lower canopy resistances of (a) one-layer and (b) three-layer models. LET was the latent heat flux for the whole canopy (W m\(^{-2}\)), \( T_s \) was the surface temperature of the paddy field (°C), \( r_a \) was the aerodynamic resistance to the transfer of sensible heat between the whole rice canopy and water surface (s m\(^{-1}\)), \( r_{cg} \) was the total canopy resistance consists of rice canopy resistance and water surface resistance (s m\(^{-1}\)), \( LE_p \) was the latent heat flux on a panicle (W m\(^{-2}\)), \( LE_{c1} \) was the latent heat flux between upper layer rice canopy and atmosphere (W m\(^{-2}\)), \( LE_{c2} \) was the latent heat flux between lower layer rice canopy and atmosphere (W m\(^{-2}\)), \( LE_g \) 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), \( T_p \) was the water temperature (°C), \( r_{a1} \) was the aerodynamic resistance to the transfer of sensible heat between panicle and atmosphere (s m\(^{-1}\)), \( r_{a2} \) was the aerodynamic resistance to the transfer of sensible heat between upper layer rice canopy and atmosphere (s m\(^{-1}\)), \( r_{a3} \) was the aerodynamic resistance to the transfer of sensible heat between lower layer rice canopy and atmosphere (s m\(^{-1}\)), \( r_{g1} \) was the panicle transpiration resistance (s m\(^{-1}\)), \( r_{g2} \) was the lower layer canopy resistance (s m\(^{-1}\)), \( r_{g3} \) was the upper layer canopy resistance (s m\(^{-1}\)), \( r_{g4} \) was the aerodynamic resistance to the transfer of sensible heat between lower layer rice canopy and atmosphere (s m\(^{-1}\)), \( r_{g5} \) was the aerodynamic resistance to the transfer of sensible heat between upper layer rice canopy and atmosphere (s m\(^{-1}\)), \( r_{g6} \) was the aerodynamic resistance to the transfer of sensible heat between water surface and atmosphere (s m\(^{-1}\)), \( r_{g7} \) was the panicle transpiration resistance (s m\(^{-1}\)), \( r_{g8} \) was albedo of water surface (s m\(^{-1}\)).]
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 $T_g = T_a$ in the model), $e_{sat}(T_g)$ 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 and lower canopy layer (50–100 cm) and lower canopy layer (10–40 cm) were written from equations (8) to (10c):

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

(8)

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

(9a)

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

(9b)
Table 1: Input parameters required for the calculation in the three-layer model.

| Symbol | Name                                      | Unit          |
|--------|-------------------------------------------|---------------|
| $R_n$  | Net radiation for the whole canopy        | W m$^{-2}$    |
| $G$    | Soil heat flux                            | W m$^{-2}$    |
| $L_d$  | Downward long-wave radiation for the whole canopy | W m$^{-2}$ |
| $L_u$  | Upward long-wave radiation for the whole canopy | W m$^{-2}$ |
| $T_a$  | Air temperature                           | °C            |
| $e_a$  | Water vapor pressure of the air           | hPa           |
| $u$    | Wind speed                                | m s$^{-2}$    |
| $T_c$  | Water temperature                         | °C            |
| $d_w$  | Water depth                               | m             |
| $H_{c2}$ | Latent heat flux between water surface beneath canopy and atmosphere | W m$^{-2}$ |

Forcing parameters

| Symbol | Name                                      | Unit          |
|--------|-------------------------------------------|---------------|
| $a_1$  | Green leaf and yellow leaf area index in the upper canopy layer | m$^2$ m$^{-3}$ |
| $a_2$  | Green leaf and yellow leaf area index in the lower canopy layer | m$^2$ m$^{-3}$ |
| PAR    | Photosynthetically active radiation       | μmol m$^{-2}$ s$^{-1}$ |
| $g_s$  | Stomatal resistance                       | cm s$^{-1}$   |

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

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

$$LE_{c1} + LE_{c2} = LE_T - LE_P, \quad (10a)$$

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

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

where $LE_{c1}$ and $LE_{c2}$ were the latent heat flux between upper and lower layer canopy and atmosphere (W m$^{-2}$), respectively. $H_{c2}$ and $H_s$ 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 $r_a$, $r_{rag}$, $r_{ac1}$, and $r_{ac2}$ was expressed in the following equation:

$$\frac{1}{r_a} = \frac{1}{r_{rag}} + \frac{1}{r_{ac1}} + \frac{1}{r_{ac2}}. \quad (11)$$

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):

$$r_{c1} = \frac{1}{(g_s a_1)}, \quad (12a)$$

$$r_{c2} = \frac{1}{(g_s a_2)}, \quad (12b)$$

$$g_s = \frac{m_s PAR + (g_{s\text{max}} - g_{s\text{min}})}{2n_s} + g_{s\text{min}} - \frac{1}{2n_s \times [m_s PAR + (g_{s\text{max}} - g_{s\text{min}})]^2 - 4m_s PAR (g_{s\text{max}} - g_{s\text{min}}) n_s^{1/2}]. \quad (13)$$

where $g_s$ was the stomatal conductance (cm s$^{-1}$), $m_s$ and $n_s$ were parameters, PAR was photosynthetically active radiation (μmol m$^{-2}$ s$^{-1}$), $g_{s\text{max}}$ was the maximum of stomatal conductance (cm s$^{-1}$), and $g_{s\text{min}}$ 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 ($R_{n\text{p}}$) 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):

$$R_{in} = (1 - 0.35)F_p(\sec \theta S_d + 2d_f S_f) + F_pd_f(L_d + L_a),$$  
(14a)

$$R_{in} = 2F_pd_f \sigma T_p^4 + H_p + LE_p,$$  
(14b)

$$L_d = \alpha T_{c1}^4 + (L_d - \alpha T_{c1}^4) \exp(-F_1a_1d_f),$$  
(15a)

$$L_a = \alpha T_{c2}^4 + (\alpha T_{c2}^4 - \alpha T_{c1}^4) \exp(-F_2a_2d_f) + \sigma T_{c1}^4 + (\sigma T_{c2}^4 - \sigma T_{c1}^4) \exp(-F_1a_1d_f),$$  
(15b)

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:

$$H_p = \frac{c_p(F_p(T_p - T_{ac1}))}{r_{ap}},$$  
(16a)

$$LE_p = \frac{c_p(e_{sat}(T_p) - e(T_{ac1}))}{[\gamma(r_{ap} + r_p)]},$$  
(16b)

$$\frac{(T_{c1} - T_{ac1})}{r_{c1}} = \frac{(T_{ac1} - T_a)}{r_{ac1}}.$$  
(17)

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):

$$T_{ac1} = \frac{(r_{ac1}T_{c1} + r_{ac1}T_a)}{(r_{c1} + r_{ac1})},$$  
(18a)

$$e_{ac1} = \frac{(r_{ac1}T_{c1} + r_{ac1}e_a)}{(r_{c1} + r_{ac1})}.$$  
(18b)

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, $T_p$ 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 IMFPACT [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

| Date       | Canopy layer | VPD (hPa) | $m_i$ (cm s⁻¹)(µ mol m⁻² s⁻¹) | $g_{s_{\text{max}}}$ (cm s⁻¹) |
|------------|--------------|-----------|-------------------------------|-------------------------------|
| August 6   | Upper        | ~18       | 0.00247                       | 1.500                         |
|            | ~18          | 0.00170   |                               | 0.500                         |
|            | ~10          | 0.002405  |                               | 1.500                         |
|            | Lower        | 10~15     | 0.002095                      | 1.200                         |
|            | 15~          | 0.001925  |                               | 0.800                         |
| August 13  | Upper        | ~8        | 0.00780                       | 0.820                         |
|            | 8~           | 0.01246   |                               | 0.410                         |
|            | ~8           | 0.009935  |                               | 0.515                         |
|            | Lower        | 8~        | 0.00833                       | 0.470                         |
| August 27  | Upper        | ~9        | 0.00282                       | 0.500                         |
|            | 9~           | 0.00195   |                               | 0.400                         |
|            | ~10          | 0.003155  |                               | 0.900                         |
|            | Lower        | 10~11     | 0.00261                       | 0.750                         |
|            | 11~          | 0.00213   |                               | 0.450                         |
| September 4| Upper        | ~16       | 0.003475                      | 0.550                         |
|           | 16~         | 0.000445  |                               | 0.400                         |
|            | ~15         | 0.001315  |                               | 0.400                         |
|            | Lower        | 15~16     | 0.00123                       | 0.400                         |
|            | ~16         | 0.00615   |                               | 0.400                         |

Note: VPD is vapor pressure deficit, $g_i$ is the stomatal conductance (cm s⁻¹), $g_{s_{\text{max}}}$ is the maximum of stomatal conductance (cm s⁻¹), $m_i$ is the minimum of 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 \( T_c \) and \( T_p \) 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 \( (S_g) \) was 262 W m\(^{-2}\), the average air temperature \( (T_a) \) was 25°C, while the highest \( T_a \) 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 \( (a_1) \) 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 \( (a_2) \) decreased from 3 on July 25 to 1.5 on August 8, 2014.

3.3. Modeling Parameter Results

3.3.1. Parameters \( F_1, F_2, \) and \( F_F \). From August 5 to September 7 in the ripening stage, there was a little diurnal variation of rice morphology.

\( F_1 \) was smaller than \( F_2 \) because the transmissivity of solar radiation was larger in the upper layer, and the leaf area index of the upper layer canopy \( (a_1) \) was also bigger than that in the lower layer \( (a_2) \). For example, \( a_1 \) was 2.5 and \( a_2 \) was 1.5 on August 8. \( F_1 \) and \( F_2 \) 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
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 ($S_o$, $T_o$, 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 $r_{aw}$, $r_{agr}$, 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 ($S_o$, $T_{a1}$, $u$, 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 $-1.69^\circ$C to $1.35^\circ$C and from $-1.50^\circ$C to $1.61^\circ$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

| Date       | Time | $T_p$ (°C) | $T_{a1}$ (°C) | $u$ (m s$^{-1}$) | $r_{ap}$ (s m$^{-1}$) |
|------------|------|------------|---------------|------------------|-------------------|
| August 5   | 8:30 | 26.8       | 27.8          | 0.4              | 18.1              |
| August 7   | 8:30 | 26.8       | 28.4          | 0.6              | 10.9              |
| August 18  | 8:30 | 26.3       | 26.9          | 0.6              | 10.9              |
| August 26  | 9:30 | 26.1       | 27.6          | 1.7              | 6.2               |
| August 28  | 8:30 | 24.7       | 25.1          | 0.6              | 12.4              |

Note: $r_{ap}$ is the aerodynamic resistance to the transfer of sensible heat between panicle and atmosphere, $T_p$ is the panicle temperature, $T_{a1}$ is the air temperature at the panicle’s height, and $u$ is the wind speed.

Table 3: $r_{ap}$ in the rice paddy field.

![Figure 5](image-url) Relationship between wind speed ($u$) and aerodynamic resistance to the transfer of sensible heat between panicle and atmosphere ($r_{ap}$) in the rice paddy field on August 5, 7, 18, 26, and 28, 2014 (a). Change of panicle transpiration resistance ($r_p$) against the days after heading (DAH) in the rice paddy field on August 12, 18, 19, and 31 and September 2, 2014 (b).
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
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) $T_c$ instead of $T_p$ was used to predict $T_p$, since modelled $T_c$ could be 3°C different with modelled $T_p$; (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.

### Table 5: $T_p$ estimated by three-layer model and by IM$^2$PACT [30].

| Date      | Time  | $S_i$ (W m$^{-2}$) | $T_a$ (°C) | RH (%) | $T_c$ (°C) | $T_1$ (°C) | $T_2$ (°C) | $T_p$ by IM$^2$PACT (°C) | $T_p$ by three-layer model (°C) | Mea $T_p$ (°C) |
|-----------|-------|-------------------|------------|--------|-----------|-----------|-----------|------------------------|-------------------------------|----------------|
| August 5  | 9:00  | 212               | 28         | 80     | 26.7      | 26.2      | 28.9      | 26.6                   | 26.8                          |
| August 5  | 14:00 | 201               | 30         | 71     | 28.1      | 26.9      | 27.6      | 26.9                   | 27.0                          |
| August 11 | 11:00 | 671               | 27         | 73     | 28.9      | 25.5      | 27.0      | 25.2                   | 25.7                          |
| August 18 | 9:00  | 235               | 27         | 84     | 26.3      | 25.8      | 26.7      | 26.2                   | 26.3                          |
| August 18 | 12:00 | 599               | 31         | 68     | 26.8      | 29.5      | 27.4      | 28.4                   | 28.4                          |
| August 18 | 15:00 | 485               | 32         | 68     | 28.5      | 26.7      | 29.7      | 28.8                   | 28.7                          |
| August 19 | 9:00  | 477               | 32         | 66     | 28.2      | 26.1      | 29.8      | 28.5                   | 28.9                          |
| August 19 | 14:00 | 745               | 32         | 66     | 28.5      | 30.5      | 28.6      | 29.6                   | 30.1                          |
| August 19 | 16:00 | 541               | 33         | 59     | 28.5      | 28.9      | 28.5      | 29.3                   | 29.1                          |
| August 20 | 17:00 | 188               | 29         | 77     | 28.3      | 26.4      | 28.9      | 27.8                   | 27.7                          |
| August 20 | 18:00 | 80                | 29         | 78     | 27.7      | 25.1      | 27.2      | 26.5                   | 26.6                          |
| August 26 | 12:00 | 474               | 29         | 67     | 27.6      | 26.5      | 25.7      | 27.4                   | 27.0                          |
| August 26 | 15:00 | 442               | 30         | 69     | 28.2      | 26.4      | 30.3      | 27.5                   | 28.1                          |
| September 3| 15:00 | 86                | 29         | 70     | 27.2      | 25.2      | 29.1      | 26.5                   | 27.1                          |
| September 6| 10:00 | 474               | 29         | 71     | 26.7      | 24.9      | 28.1      | 25.7                   | 26.7                          |
| September 6| 16:00 | 93                | 28         | 76     | 29.3      | 28.8      | 27.8      | 30.1                   | 29.3                          |

Note: Mea means measured.

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

| Temperature | RMSE (°C) | MAE (°C) | SD (°C) |
|-------------|-----------|----------|---------|
| $T_c$ estimated by three-layer model | 0.73 | 0.81 | 0.64 |
| $T_c$ estimated by two-layer model | 1.21 | 1.56 | 1.25 |
| $T_1$ estimated by three-layer model | 0.76 | 0.75 | 0.74 |
| $T_2$ estimated by three-layer model | 0.75 | 0.63 | 0.98 |
| $T_p$ estimated by three-layer model | 0.81 | 0.7 | 0.67 |
| $T_p$ estimated by IM$^2$PACT | 1.27 | 0.95 | 0.76 |

Note: $T_c$ is the canopy temperature (°C); two-layer model is developed by Yan and Oue [38]; $T_1$ and $T_2$ 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.
Disclosure

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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