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学位論文全文に代わる要約
Extended Summary in Lieu of Dissertation

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学位論文題目：
Title of Dissertation　　Study on micrometeorological environment and the modeling in rice paddy fields
（水田における微気象環境とそのモデル化に関する研究）

学位論文要約：
Dissertation Summary

Abstract

In this study, the effects of micrometeorological conditions and vegetational factors, such as solar radiation (*St*), vapor pressure deficit (VPD), growth stage and canopy resistance (r_c) on the energy budget in the rice paddy field were assessed. With predicted global warming, the effects of climate change on rice growth have become major concerns, and we conducted water ponding experiments to decrease leaf temperature (T_l) and panicle temperature (T_p) in two rice paddy fields. Panicle temperature (T_p) is critically important for the heat damage, so a model is necessary to continuously monitor T_p. Since panicle exists not in whole canopy but mostly in the upper layer canopy, and we developed three-layer model, which consists of upper and lower canopy layers and water surface layer to predict T_p. The better agreements between measured and calculated canopy temperature (T_c) and T_p have indicated the three-layer model is a more reliable tool to predict T_c compared with two-layer model or paddy thermal prediction model, and to predict T_p compared with integrated micrometeorology model for panicle and canopy temperature (IM^{2}PACT).

1. Introduction

Rice (*Oryza sativa* L.) is one of the most important crops worldwide, and given reasonable supplies of water, solar radiation (*St*) and air temperature (T_a) are the major natural resources which control the productivity of rice. Effects of *St* and the canopy resistance (r_c) on the energy budget in the rice paddy field were assessed. The effect of T_a on rice growth and yield has two aspects: growth is stimulated by an increase of T_a up to 30 ℃, but high temperature because of predicted global warming leads to yield decrease due to heat induced sterility.

To mitigate high temperature damage, we conducted water ponding experiments to decrease leaf temperature (T_l) and panicle temperature (T_p) in two rice paddy fields. The organ susceptive to high temperature is panicle and panicle temperature (T_p) is critically important for the heat damage, so a model is necessary to continuously monitor T_p. In the heat balance equation on the panicle, longwave radiations from a leaf surface adjacent to the panicle and from the atmosphere are necessary. To date, the whole canopy temperature (T_c) predicted by two-layer model has been used to calculate the longwave radiations to the panicle. But panicle exists not in whole canopy but mostly in the upper layer canopy, and we have proved that T_c is different from the upper canopy temperature (T_{c1}), so the upper layer must be separated from the whole canopy for the purpose of predicting T_p. Therefore, we developed three-layer model, which consists of upper and lower canopy layers and water surface layer to predict T_p.

2. Material and methods

2.1 Micrometeorological measurements

In 2013, black rice was transplanted in the paddy field located in the Faculty of Agriculture, Ehime University, Matsuyama, Japan (33°50′N, 132°47′E). We measured solar radiation (St), air temperature (T_a), relative humidity (RH), wind speed (u), water depth (d_w), water temperature (T_w), plant height (PH) and leaf area index (LAI). In 2014, besides these meteorological conditions and vegetational factors, we also measured solar radiation within rice canopy in every 10 cm layer, downward and upward longwave radiations beneath the rice canopy in two paddy fields located in the Ehime University Senior High School, Matsuyama, Japan (33°50′N, 132°47′E).

2.2 Experiments in the plots in 2014

An experimental plot was set from July 8 to September 8, 2014 within the first conventionally water managed paddy field (cultivar. ‘Akitakomachi’), and the other experimental plot was set within the second conventionally water managed paddy field (cultivar. ‘Nikomaru’) from September 9 to 30 in 2014, and water ponding was conducted in both plots every day. T_l and T_p in the water ponding plot ($T_{l(WP)}$ and $T_{p(WP)}$) and conventionally water managed paddy field ($T_{l(Con)}$ and $T_{p(Con)}$), were measured every two or three hours during daytime in every 10 cm canopy layer every day. Water surface evaporation beneath the rice canopy was measured by the lysimeter twice (8:30 and 18:30) every day.

2.3 Three-layer model

The schematic representation of three-layer model developed based on the two-layer model proposed by Yan and Oue (2011) is shown in Fig. 1.

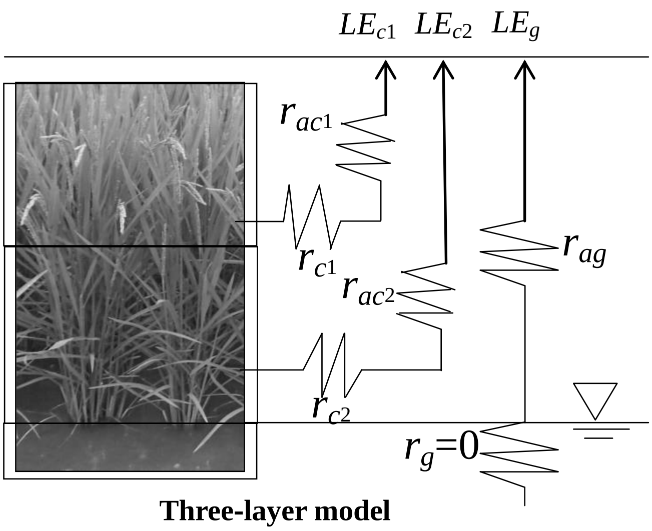


Fig. 1 A schematic representation of the aerodynamic resistance, upper and lower canopy resistance by three-layer model.

The energy budget equations for upper and lower canopy layers are as shown from Eq. (1) to Eq. (4).

$$Rn_{c1} + Rn_{c2} = H_{c1} + LE_{c1} + H_{c2} + LE_{c2} \tag{1}$$

$$c_p \rho \left[(T_{c1} - T_a)/r_{ac1} + (T_{c2} - T_a)/r_{ac2} \right] = H - H_g \tag{2}$$

$$c_p \rho \left[e_{sat}(T_{c1}) - e_a \right] / [\gamma (r_{c1} + r_{ac1})] + c_p \rho \left[e_{sat}(T_{c2}) - e_a \right] / [\gamma (r_{c2} + r_{ac2})] = LET - LE_g \tag{3}$$

$$1/r_a = 1/r_{ag} + 1/r_{ac1} + 1/r_{ac2} \tag{4}$$

where Rn_{c1} and R_{n2} are net radiation absorbed by upper and lower canopy layers (W m^{-2}), H_{c1} and H_{c2} are sensible heat flux of upper and lower canopy layers (W m^{-2}), LE_{c1} and LE_{c2} are latent heat flux of upper and lower canopy layers (W m^{-2}), H_g is sensible heat flux of water surface (W m^{-2}), LE_g is latent heat flux of water surface (W m^{-2}) measured by the lysimeter, T_{c1} and T_{c2} are upper and lower canopy temperatures (℃), r_{ac1} and r_{ac2} are aerodynamic resistance between upper canopy and atmosphere, between lower canopy and atmosphere (s m^{-1}), r_{c1} and r_{c2} are upper and lower canopy resistance (s m^{-1}), calculated by stomatal resistance (g_s) and LAI of each layer.

The radiation input to a panicle (R_{in}) is the sum of shortwave and longwave radiations absorbed by the panicle (Eq. (5a)), and the heat balance in the panicle can be written as Eq. (5b).

$$R_{in}=(1-\alpha_p)F_p(\sec\theta S_d+2d_fS_f)+F_pd_f\left[\sigma T_{c1}^4+(Ld-\sigma T_{c1}^4)\exp(-F_1a_1d_f)+\sigma T_{c2}^4+(\sigma T_g^4-\sigma T_{c2}^4)\exp(-F_2a_2d_f)\right] \quad (5a)$$

$$R_{in}=2F_pd_f\sigma T_p^4+c_p\rho(T_p-T_{ac1})/r_{ap}+c_p\rho[e_{sat}(T_p)-e(T_{ac1})]/\left[\gamma\left(r_{ap}+r_p\right)\right] \quad (5b)$$

where α_p is albedo of panicle, F_p is the inclination factor of the panicle, θ is solar zenith angle, d_f is diffusivity factor (=1.66), S_d is downward direct solar radiation (W m^{-2}), S_f is diffuse solar radiation (W m^{-2}), the ratio of which to *St* is set to 0.5, *Ld* is downward longwave radiation from atmosphere (W m^{-2}), F_1 and F_2 are inclination factors of leaves in the upper and lower canopy layers, T_p is panicle temperature (℃), r_{ap} is aerodynamic resistance between the panicle and atmosphere (s m^{-1}), r_p is panicle resistance for transpiration (s m^{-1}), T_{ac1} and e_{ac1} are the air temperature and humidity at the panicle's height, which were calculated from the resistance of the pathways of sensible and latent heat fluxes according to the Ohm's law as follows.

$$T_{ac1}=\left(r_{ac1}T_{c1}+r_{c1}T_a\right)/\left(r_{c1}+r_{ac1}\right) \quad (6a)$$

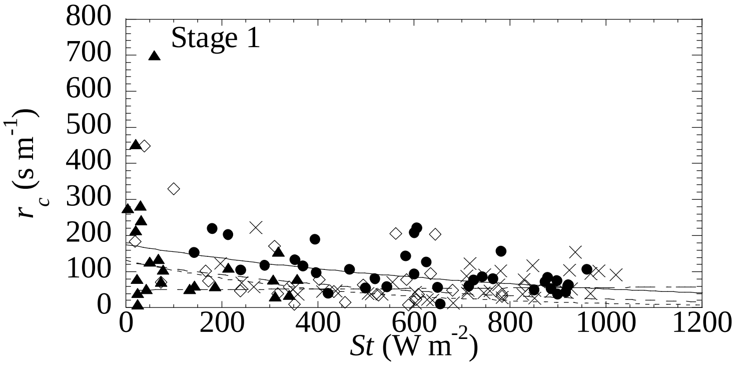
$$e_{ac1}=\left(r_{ac1}T_{c1}+r_{c1}e_a\right)/\left(r_{c1}+r_{ac1}\right) \quad (6b)$$

The r_{ap} was parameterized by wind speed firstly, then r_p was parameterized by days after heading, and T_p could be lastly calculated by combining equations above.

3. Results and discussion

3.1 Micrometeorological conditions and vegetational factors influence the energy balance

The relationships between solar radiation (*St*) and canopy resistance (r_c) classified by four ranges of vapor pressure deficit (VPD) are shown in Fig. 2. Under higher *St*, r_c was influenced by VPD more, and stomata of a big leaf tended to be more sensitive to the decrease of *St* under high VPD conditions.



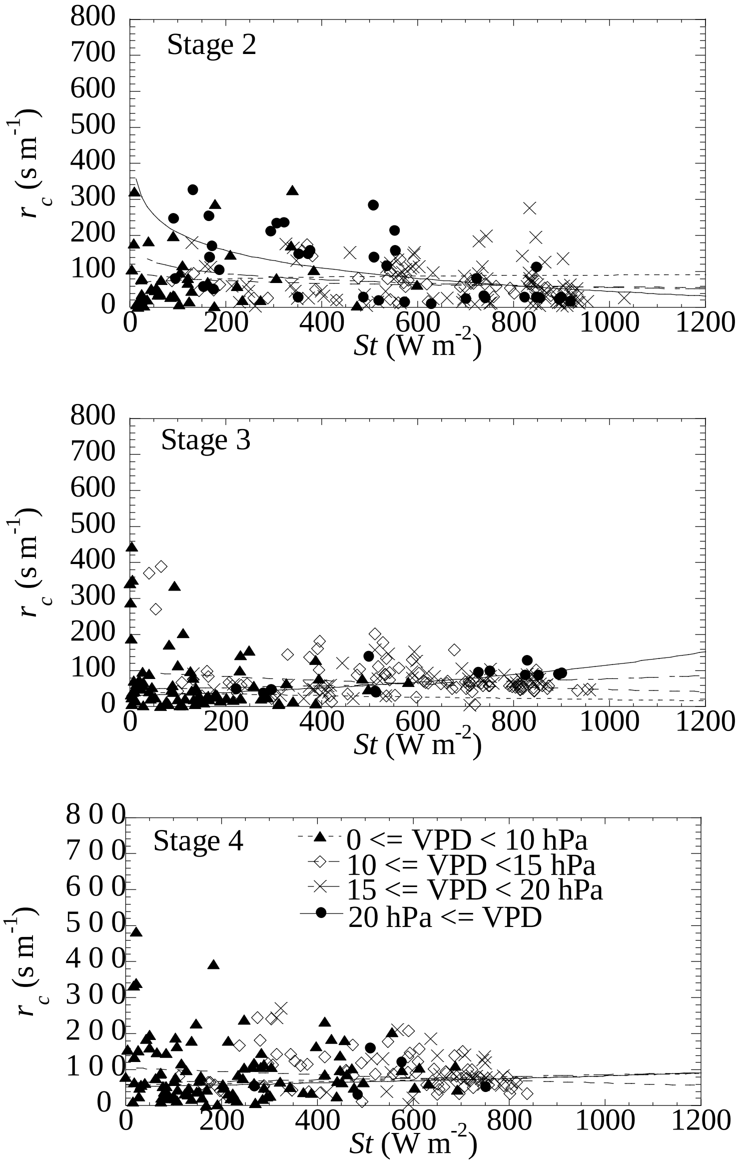


Fig. 2 Relationships between solar radiation (*St*) and canopy resistance (r_c) classified by four ranges of vapor pressure deficit (VPD).

Relationships between r_c and Bowen ratio (*Bo*) classified by four growing stages are shown in Fig. 3. In each stage, there was no clear relationship between r_c and *Bo* (correlation coefficient was less than 0.01). Therefore, we concluded r_c did not account for energy partitioning directly. Critical canopy resistance (r_{cc}) was defined as canopy resistance when *Bo* was zero. The relationships between *St* and r_{cc} classified by four ranges of VPD showed that with the increase of *St*, r_{cc} decreased (Fig. 4). The difference between canopy resistance and critical canopy resistance (r_c-r_{cc}) had the linear relationship with *Bo* in each stage (Fig. 5). So it was r_c-r_{cc} that accounted for the energy partitioning directly.

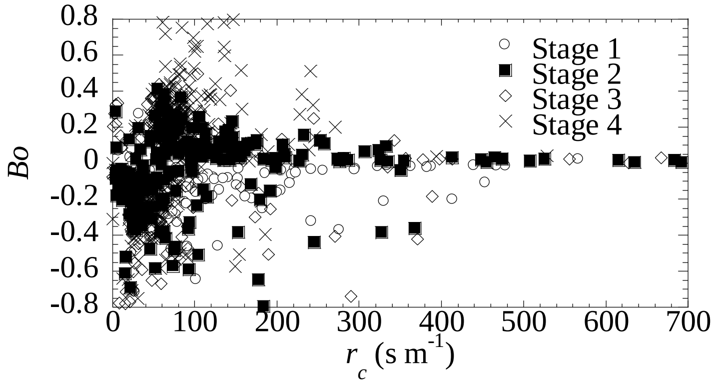


Fig. 3 Relationships between canopy resistance (r_c) and Bowen ratio (*Bo*) classified by four growing stages.

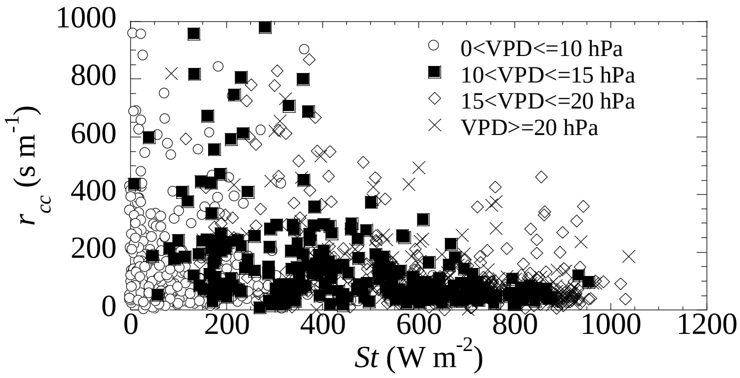


Fig. 4 Relationships between solar radiation (*St*) and critical canopy resistance (r_{cc}) classified by four ranges of vapor pressure deficit (VPD).

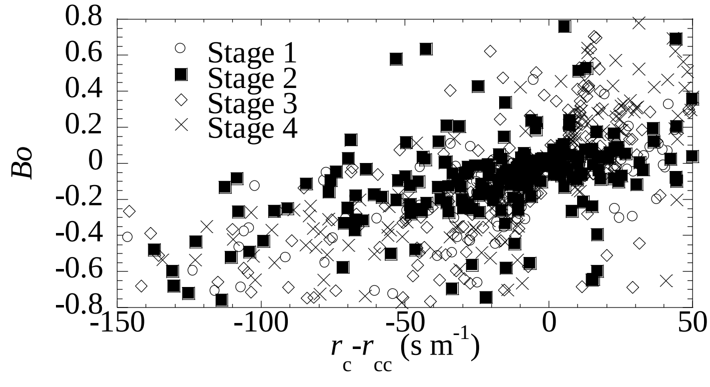


Fig. 5 Relationships between r_c-r_{cc} and Bowen ratio (*Bo*) classified by four growing stages.

3.2 Leaf temperature (T_l) and panicle temperature (T_p)

Examples of T_l and T_p in two experimental paddy fields under clear conditions are shown from Fig. 6

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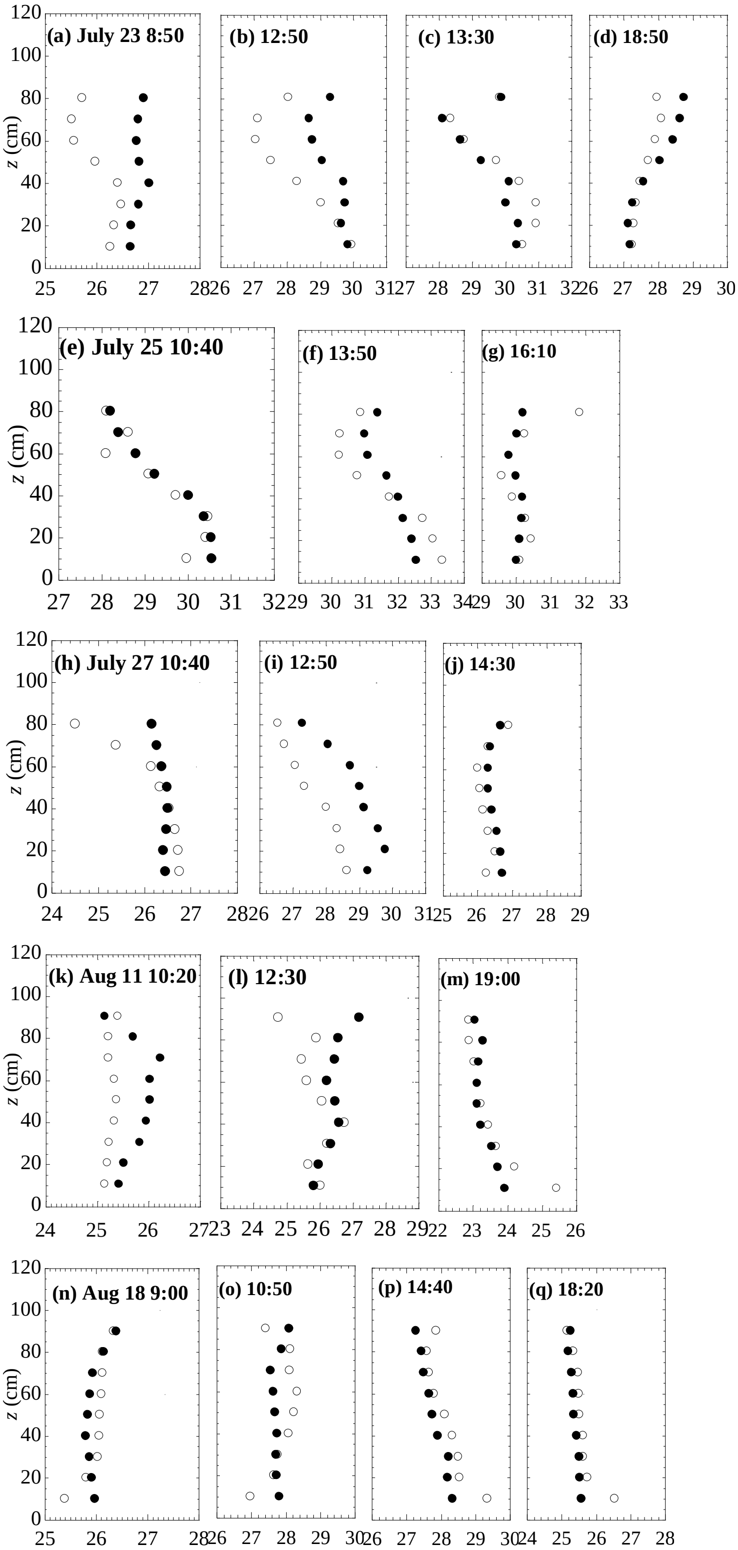
to Fig. 9.



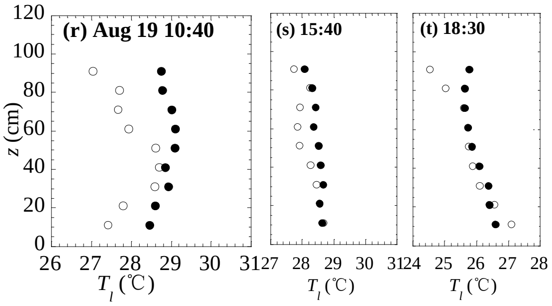


Fig. 6 Leaf temperature (T_l) in the first experimental paddy field (○; $T_{l(WP)}$ and ●; $T_{l(Con)}$): July 23 (a-d), July 25 (e-g), July 27 (h-j), August 11 (k-m), August 18 (n-q) and August 19 (r-t), 2014.

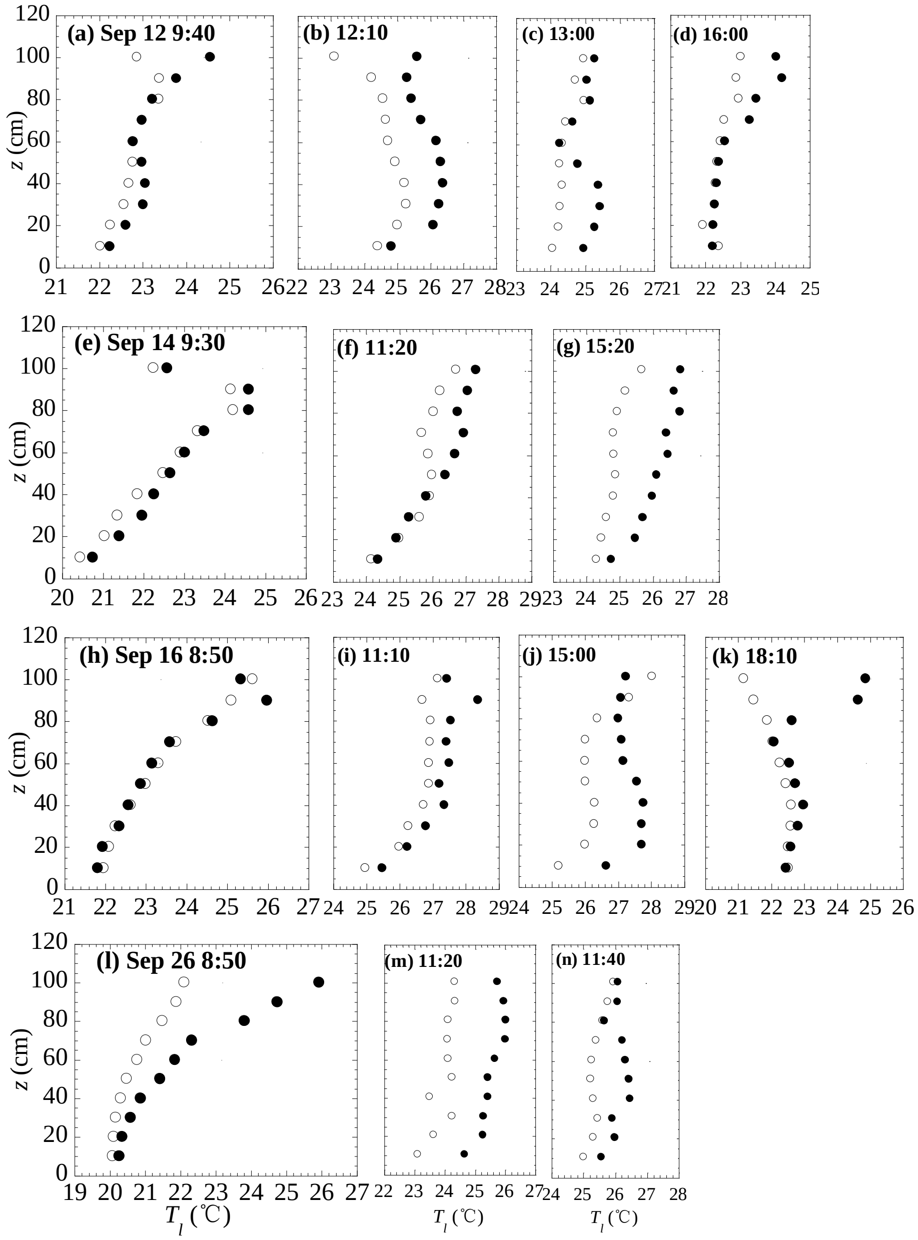


Fig. 7 Leaf temperature (T_l) in the second experimental paddy field (○; $T_{l(WP)}$ and ●; $T_{l(Con)}$): September 12 (a-d), September 14 (e-g), September 16 (h-k) and September 26 (l-n), 2014.

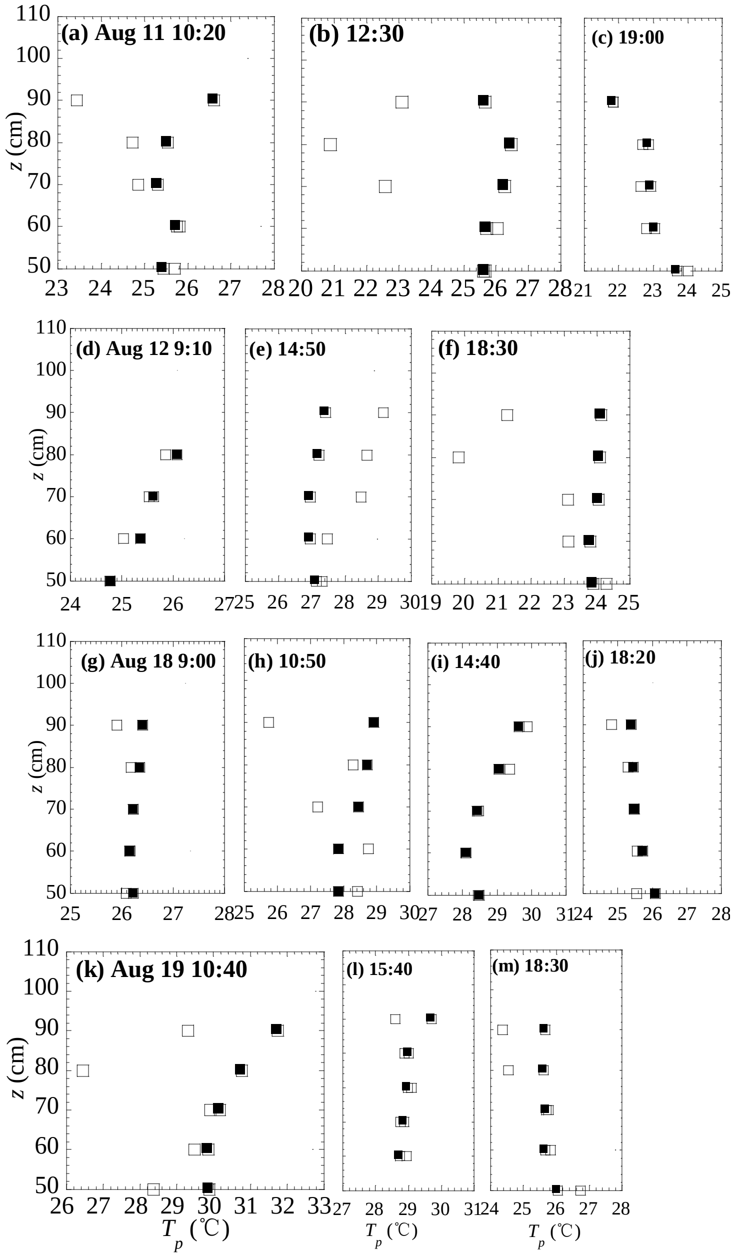
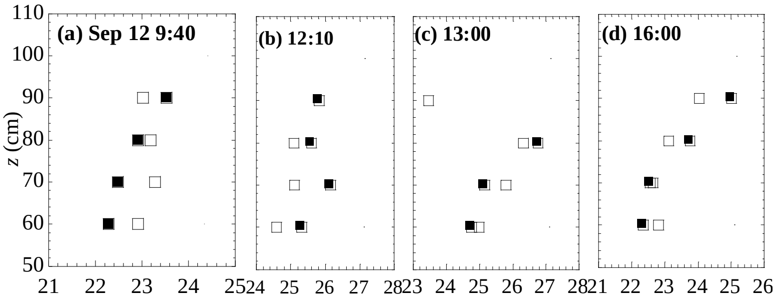


Fig. 8 Panicle temperature (T_p) in the first experimental paddy field (□; $T_{p(WP)}$ and ■; $T_{p(Con)}$): August 11 (a-c), August 12 (d-f), August 18 (g-j) and August 19 (k-m), 2014.



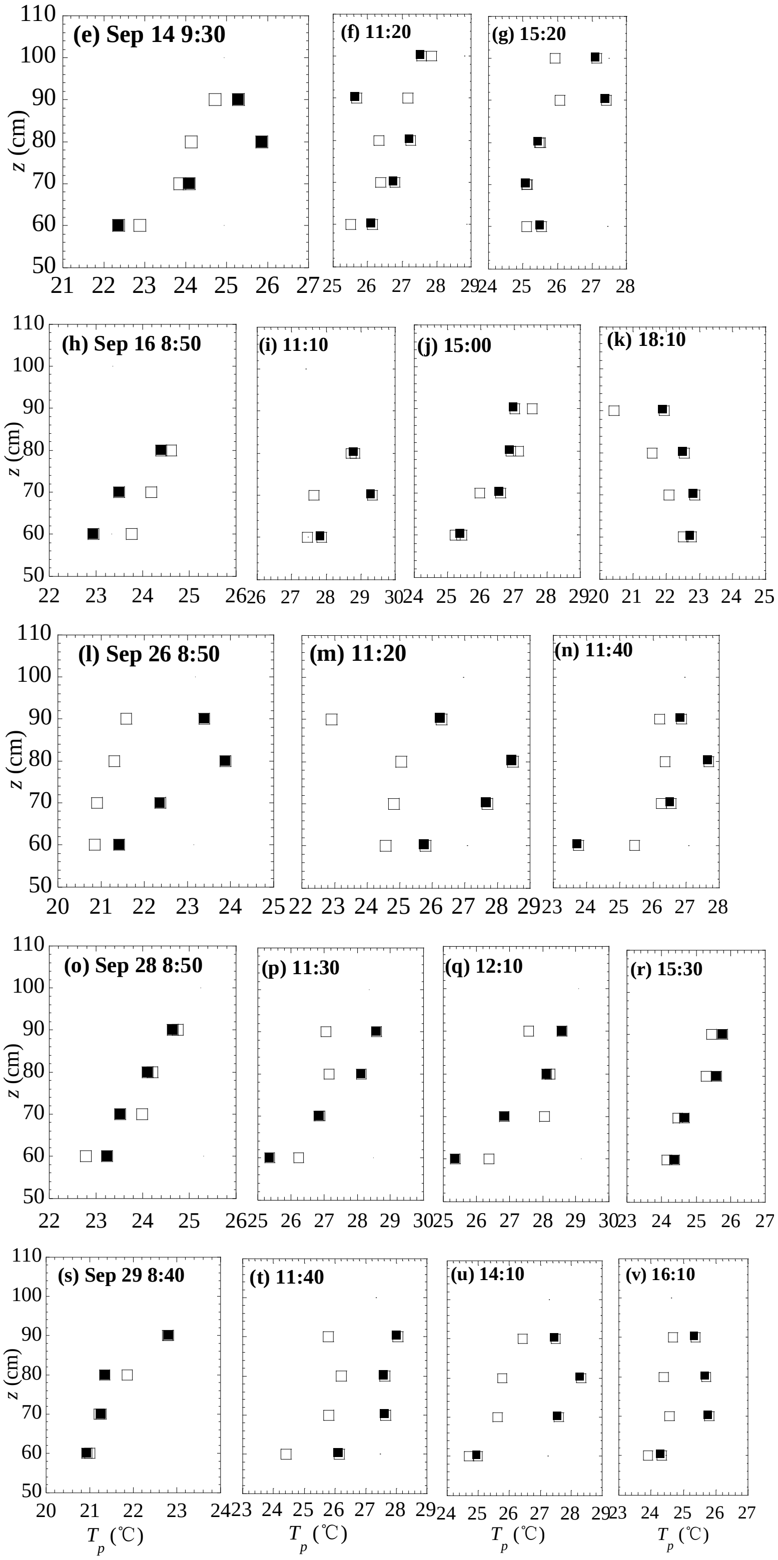


Fig. 9 Panicle temperature (T_p) in the second experimental paddy field (□; $T_{p(WP)}$ and ■; $T_{p(Con)}$): September 12 (a-d), September 14 (e-g), September 16 (h-k), September 26 (l-n), September 28 (o-r) and September 29 (s-v), 2014.

As shown in the figures, water ponding decreased T_l and T_p consistently in the plots during daytime as a whole. And the average $T_{l(WP)}$-$T_{l(Con)}$ and $T_{p(WP)}$-$T_{p(Con)}$ in every 10 cm layer in two experimental paddy fields are shown in Table 1.

Table 1 Average $T_{l(WP)}$-$T_{l(Con)}$ and $T_{p(WP)}$-$T_{p(Con)}$ in two experimental paddy fields in 2014.

z (cm)	First experimental paddy field				Second experimental paddy field			
	Number of data	$T_{l(WP)}$-$T_{l(Con)}$	Number of data	$T_{p(WP)}$-$T_{p(Con)}$	Number of data	$T_{l(WP)}$-$T_{l(Con)}$	Number of data	$T_{p(WP)}$-$T_{p(Con)}$
10	86	-0.58	76	-	45	-0.39	43	-
20	86	-0.53	76	-	45	-0.51	43	-
30	86	-0.48	76	-	45	-0.52	43	-
40	86	-0.53	76	-	45	-0.52	43	-
50	86	-0.51	76	-0.63	45	-0.53	43	-
60	86	-0.54	76	-0.48	45	-0.58	43	-0.20
70	86	-0.57	76	-0.57	45	-0.60	43	-0.60
80	86	-0.72	76	-1.06	45	-0.63	43	-0.58
90	86	-0.83	76	-1.31	45	-0.75	43	-1.04
100		-		-	45	-1.14	43	-0.46

In the first experimental paddy field, $T_{l(WP)}$ and $T_{p(WP)}$ could be 0.83 ℃ and 1.31 ℃ lower than $T_{l(Con)}$ and $T_{p(Con)}$, respectively. And in the second experimental paddy field, $T_{l(WP)}$ and $T_{p(WP)}$ could be 1.14 ℃ and 1.04 ℃ lower than $T_{l(Con)}$ and $T_{p(Con)}$, respectively.

Nishida *et al*. (2014) conducted continuous irrigation with cool running-water experiments in a paddy field during the rice ripening period, and measured water temperature (T_w) by copper-constantan thermocouple and whole canopy temperature (T_c) by infrared thermometer at three points. The number of measured data was limited (daytime: 8 and nighttime: 12) compared with our measurements of T_l in two experimental paddy fields: 86 and 45, respectively. And R-square values of the linear regression equations for water temperature difference (δT_w) and rice temperature difference (δT_c) at 30 cm, 50 cm, 70 cm and 90 cm among the points were low (0.70, 0.28, 0.19 and 0.06), which meant it could not evaluate effects of this water management on decreasing plant temperature reliably and directly as our study.

In the water ponding plot, the water depth (d_w) was larger than that in the conventionally water managed paddy field, in which water supply form soil could not meet the demand from atmosphere, so $T_{l(Con)}$ was higher than $T_{l(WP)}$ because transpiration was reduced. The lower $T_{l(WP)}$ led to the smaller longwave radiations from leave and atmosphere to the panicle, so $T_{p(WP)}$ was also lower than $T_{p(Con)}$.

3.3 Parameters F_1, F_2 and F_p

F_1, F_2 and F_p were decided by fitting the calculated transmissivity of downward solar radiation (TDSR) to the measured TDSR. The average hourly F_1, F_2 and F_p of all the measurements are presented in Fig. 10.

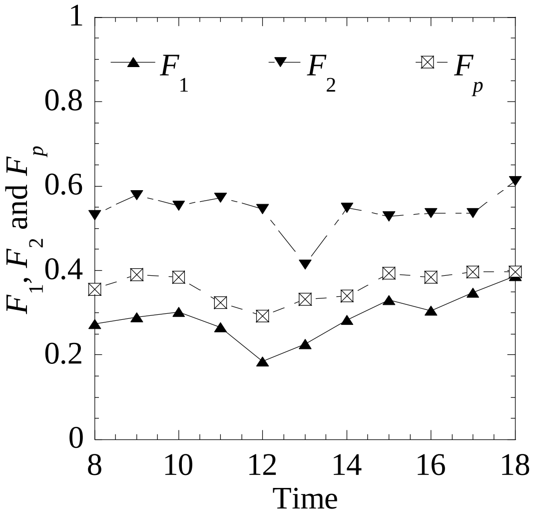


Fig. 10 Variations of F_1, F_2 and F_p from 8:00 to 18:00 in the first experimental paddy field from August 5 to September 7, 2014.

F_1 and F_2 were larger in the morning and afternoon than those near noon, which was caused by the different solar radiation altitudes. The variation of F_p was similar with that of F_1 from morning to afternoon because of the similar form of panicles and leaves.

3.4 Aerodynamic resistance between the panicle and atmosphere (r_{ap})

When the panicle is under completely wet condition, panicle resistance for transpiration (r_p) is considered as 0, and r_{ap} can be calculated with measured T_p. As a result of correlation analysis between meteorological conditions (St, T_a, RH and u) and r_{ap}, it was found that r_{ap} was primarily influenced by u with the correlation coefficient of -0.93. It was similar with the results reported by Yan and Oue (2011) which showed that u was the main influencing factor for r_a, r_{ag} and r_{ac} (aerodynamic resistance between rice canopy and atmosphere). The relationship between u and r_{ap} can be drawn as

$$r_{ap} = 6.2724/u \tag{7}$$

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 is primarily due to molecular diffusion.

3.5 Panicle resistance for transpiration (r_p)

With the measured T_p and calculated r_{ap}, r_p can be calculated by the Eq. (5a, b). Correlations between days after heading (DAH), meteorological conditions (St, T_a, RH and u) and r_p showed that DAH was the main influencing factor, with correlation coefficient 0.92. The r_p increases asymptotically as the increase of DAH, and the relationship can be drawn as

$$r_p = 2.3175\exp(0.0579\mathrm{DAH}) \tag{8}$$

3.6 Modeling the panicle temperature (T_p)

The model was run with hourly time step and hourly observation of micrometeorological conditions from August 5 to September 7, 2014. The average values of measured canopy temperature from 50 cm to 100 cm, from 10 cm to 40 cm were set as the measured T_{c1} and T_{c2}, which were compared with the calculated ones as shown in Fig. 11 (a) and (b).

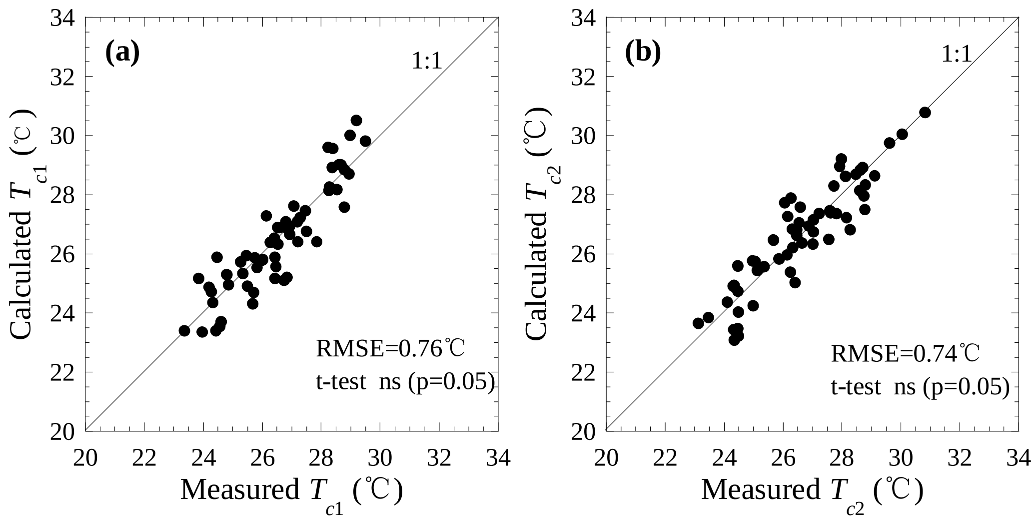


Fig. 11 Comparisons between the measured and calculated T_{c1} (a) and T_{c2} (b) in the first experimental paddy field from August 5 to September 7, 2014.

The root mean square error (RMSE) of calculated T_{c1} and T_{c2} were 0.76 ℃ and 0.75 ℃. And the difference between measured and calculated T_{c1} and T_{c2} ranged from -1.69 ℃ to 1.35 ℃, from -1.50 ℃ to 1.61 ℃, respectively. According to the 2-tail t-test statistical analysis, the calculated T_{c1} and T_{c2} values were not significantly different from measured values at the 0.05 probability level. RMSE of T_c by our three-layer model was 0.63 ℃, which was smaller than that by the two-layer model (1.19 ℃) developed by Yan and Oue (2011). And RMSE of T_p predicted by three-layer model was 0.76 ℃, which was smaller than that by the integrated micrometeorology model for panicle and canopy temperature (IM^{2}PACT, 1.27 ℃). Matsubayashi *et al*. (2013) developed the paddy thermal prediction model which considering the heat transfer with water management, and the difference between measured and calculated T_c could be 2 ℃ and 1 ℃ in the daytime and nighttime, respectively.

The better agreements between measured and calculated $T_{c1,}$ T_{c2} and T_p have indicated the three-layer model is a more reliable tool to predict T_c compared with two-layer model or paddy thermal prediction model, and to predict T_p compared with IM^{2}PACT.

4. Conclusions

In this study, we assessed influences of micrometeorological conditions and vegetational factors on the energy budget in the rice paddy field, and evaluated the effects of water ponding on decreasing leaf and panicle temperatures (T_l and T_p), and developed the three-layer model to predict T_p. We can draw the following conclusions:

(1) Stomata of a big leaf tended to be more sensitive to the decrease of solar radiation (*St*) under high vapor pressure deficit (VPD) conditions.

(2) Canopy resistance (r_c) did not account for the energy partitioning directly, but the difference between r_c and critical canopy resistance (r_{cc}) accounted for the energy partitioning.

(3) Water ponding could decrease T_l and T_p consistently in the plots during daytime as a whole, and T_l and T_p could be 0.83 ℃ and 1.31 ℃, 1.14 ℃ and 1.04 ℃ lower than those in the two conventionally water managed paddy fields.

(4) The three-layer model is a more reliable tool to predict canopy temperature (T_c) compared with two-layer model or paddy thermal prediction model, and to predict T_p compared with integrated micrometeorology model for panicle and canopy temperature (IM^{2}PACT).

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(注) 要約の文量は，学位論文の文量の約１０分の１として下さい。図表や写真を含めても構いません。(Note) The Summary should be about 10% of the entire dissertation and may include illustrations.