Integrated micrometeorology model for panicle and canopy temperature (IM²PACT) for rice heat stress studies under climate change

Mayumi YOSHIMOTO[†], Minehiko FUKUOKA, Toshihiro HASEGAWA,
Misako UTSUMI, Yasushi ISHIGOOKA, and Tsuneo KUWAGATA

(Agrometeorology division, National Institute for Agro-Environmental Sciences,
3-1-3 Kannondai, Tsukuba, Ibaraki, 305–8604, Japan)

Abstract

Projected global warming is expected to increase the occurrence of heat-induced spikelet sterility (HISS) of rice (*Oryza sativa* L.). Previous chamber experiments have shown that HISS can occur where temperature at flowering time exceeds the threshold temperature of around 35°C. The occurrence of HISS is, however, difficult to predict because the thermal conditions of rice canopy can be different from the air temperature under field condition. To cope with this, we developed a simple micrometeorology model focusing canopy and panicle temperatures; IM²PACT (Integrated Micrometeorology Model for Panicle And Canopy Temperature) as a tool to be incorporated into general meteorology databases. The IM²PACT was validated by leaf transpiration retarding (RT) experiment. During their flowering stage, leaf temperature elevated by RT treatment, which caused warming and drying of the air inside the canopy, resulting in the elevation of the panicle temperature (T_p). The IM²PACT well simulated the RT experiment, and was proved to simulate not only the T_p magnitude but also the effects on T_p of leaf transpiration characteristics via changes in micrometeorology inside the canopy. The IM²PACT was applied to the meteorology dataset based on ANEMOS in order to analyse the T_p at Kanto and Tokai regions of extremely hot summer in 2007. There was a great gap in spatial distributions between the T_p and the daily maximum air temperature which is commonly used as a measure of HISS, because the difference of meteorology, especially relative humidity, among areas altered the panicle-air temperature difference. This strongly suggests that we must refer to the T_p instead of the air temperature in daily maximum, as a measure variable for HISS. The IM²PACT is a powerful tool to elucidate the T_p in the climate change impact study to bridge between the responses of crop susceptible to heat and the meteorological data.

Key words: Canopy temperature, Heat-induced spikelet sterility, Micrometeorology, Panicle temperature, Transpiration conductance.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) concluded that global temperature rise since the mid-20th century is most likely due to the observed increase in anthropogenic greenhouse gas (GHG) concentrations (IPCC, 2007a, b). The mean air temperature is projected to increase by 1.1 to 6.4°C in the end of this century depending on the GHG

emission scenarios, resulting in significant impacts on agricultural productivity. Rice (*Oryza sativa* L.) is a staple food for nearly half the world's population (Carriger and Vallee, 2007), and highly adaptive to a range of environments from the temperate to tropical climates. Previous chamber experiments, however, have shown that rice is highly susceptible to heat (e.g., Satake and Yoshida, 1978; Matsui *et al.*, 1997), and heat-induced spikelet sterility (HISS) at flowering time is the major reason for the yield loss. The projected global warming is expected to exacerbate the yield loss due to the frequent occurrence of HISS of rice.

Received; July 4, 2011.

Accepted; September 27, 2011.

[†]Corresponding Author: yoshimot@affrc.go.jp

At the same time, the elevation of the atmospheric carbon dioxide (CO₂) concentration is expected to solely exacerbate the HISS because stomatal closure under the elevated CO₂ increases the vegetation canopy temperature (e.g., Yoshimoto *et al.*, 2005a).

According to previous studies, the threshold temperature for HISS at flowering time was around 35°C (e.g., Kim *et al.*, 1996). In fact, severe rice HISS occurred in the Yangtze Valley of China during the summer of 2003 (Wang *et al.*, 2004). While, no serious yield losses have been reported in Australia where the daily maximum air temperature sometimes reaches over 40°C during the rice flowering season (Angus, 1997; Matsui *et al.*, 2007). One of the reasons of this inconsistency is expected as heat avoidance by the evaporation cooling of rice panicle/canopy evapotranspiration, which means that there is a great gap between the temperatures of the air and panicle which is the organ susceptible to the HISS.

Very early work on the panicle temperature of rice related to the HISS is done by Nishiyama (1981), where panicle temperatures were measured in the field, screenhouse, growth chambers and phytotron glasshouse rooms with various environmental conditions and the relationship between the panicle-air temperature difference and the air temperature has been presented. Sheehy *et al.* (1998) introduced the concept of a thermal burden for evaluating thermal damage by high temperature of rice spikelets. Yoshimoto *et al.* (2005b) measured the panicle temperature and canopy micrometeorology in the rice FACE (Free Air CO₂ Enrichment) experiment in Wuxi, China (31°37'N, 120°38'E) in 2003, and developed a heat balance model of relationship between the panicle temperature and the air temperature and humidity in the vicinity of panicles. Oue *et al.* (2005), in the same experiment, simulated the panicle temperature increase by elevated CO₂, and assessed the contributions of changes of the panicle transpiration conductance or micrometeorological components.

To date, these studies have clarified the determinants of the panicle temperature and modelled it using the accurate measured data inside rice canopy. However, in order for the evaluation of HISS in regional scale or under various climates in the world, which are critical issues in the prediction of the future crop production, it is essential to develop a model that can simulate the panicle temperature using general weather data, instead of the accurate measurement inside the canopy.

The objective of this study is to develop a model with simple structure to simulate the panicle temperature from general weather data, which can be easily incorporated into the common meteorology database. We combined the two models from existing results as sub-models: First is a canopy micrometeorology sub-model (Yoshimoto *et al.*, 2005a), which estimates canopy (leaf) temperature, water temperature by solving the energy balance between the atmosphere and the canopy. Second is a panicle temperature sub-model (Yoshimoto *et al.*, 2005b), which calculates panicle temperature from the heat and radiation budgets of panicle inside the canopy microclimate. By combination of two sub-models, panicle temperatures can be estimated from general weather data. The model was validated by transpiration retarding experiment in 2005, and we examined whether the effect of the changes in canopy traits such as transpiration on the panicle temperature has been well simulated by the model. And we attempted to present the differences between the temperatures of the air and panicle by exemplifying the model analysis in extremely hot summer in 2007. Based on them, we propose the necessity of the micrometeorology model application to bridge gaps between thermal environment of rice organ and the meteorological data in climate change impact study.

2. Materials and Methods

2.1 Canopy and panicle temperatures model —IM²PACT

In order to estimate the panicle temperature in rice paddy using general weather data, we developed a model; Integrated Micrometeorology Model for Panicle And Canopy Temperature (IM²PACT). This IM²PACT mainly consists of a canopy micrometeorology sub-model and a panicle temperature sub-model. The canopy micrometeorology sub-model is a bulk heat balance model between a whole canopy and the air above the canopy (based on Yoshimoto *et al.*, 2005a), which leads bulk temperatures of vegetation canopy and the water surface in paddies (see section 2.1.1). After estimating the air temperature and humidity at the panicle's position inside the canopy by their interpolating between leaves/water surface and the air above the canopy with the distributions of heat and water vapour transfer resistances (see section 2.1.2), the panicle temperature is calculated by the panicle temperature sub-model, which is a heat balance

model between panicle and the air in the vicinity of panicle (based on Yoshimoto *et al.*, 2005b) (see section 2.1.3).

The bulk heat balance model treats the bulk sources (e.g., vegetation, water, and the air) as ones with uniform characteristics. It has high advantages such as short time of calculation, small number of parameters with providing the minimum necessary heat budget structure, by which the model can be more easily handled than multi-layer models or more complex 2- or 3-dimensional models. These fit the objectives to incorporate the model into the general meteorology database and to calculate the panicle temperature at multi-points for regional scale evaluation of HISS. Panicles are, however, mixed in leaves canopy generally with different characteristics in their transpiration and geometry from leaves, which need devising to take in the bulk model. We set an approximation; leaves are much more than panicles in the vegetation canopy and the effects of panicles on canopy micrometeorology are ignored, while the leaves affect panicle temperature and transpiration via the changes in canopy micrometeorology.

Based on this approximation, the IM²PACT solves canopy micrometeorology by using the distribution of leaf transpiration conductance first, and solves heat balance for panicle by using the pre-calculated canopy micrometeorology second, in one-way, where the calculated panicle temperature and transpiration are not fed back into the canopy micrometeorology calculation. This scheme leads uncertainty into the model estimation, and it is more ideal of two-way scheme, where the panicle and the canopy micrometeorology are interactive. The one-way scheme, however, fits the objective to incorporate of the model into the meteorology database for regional scale calculation, and its error is small generally because the ratio of panicle area to total plant canopy area in flowering stage is small (e.g., Oue, 2003a), and the panicles distribute at the layer with lots of leaves. However, in case that panicle area is comparable to leaf area, or that there is a layer occupied only by panicles such as wheat, whose top of the canopy is covered by spikes without leaves, the canopy micrometeorology sub-model needs revision to include panicle (spike) transpirational conductance as well as leaf stomatal conductance for the canopy heat balance calculation.

2.1.1 Canopy micrometeorology sub-model

As a canopy micrometeorology sub-model, we used a

double-source model originally developed by Watanabe (1994), with some improvements to adapt it for use with flooded paddies by adding a shallow water layer (Yoshimoto *et al.*, 2005a). The double-source model is based on two energy budget equations: one for the vegetation canopy and another for the ground surface (in this case, the water in paddies) (see Eqs. (1), (2) in Yoshimoto *et al.*, 2005a), of which the vegetation canopy temperature (T_c) and the ground (water) surface temperature (T_g) are determined as the solutions. Details of the calculation are provided in Yoshimoto *et al.* (2005a). In this paper, the calculation process and sub-models updated thereafter such as leaf area profile and leaf transpiration conductance are briefly explained.

The profiles of leaf area and leaf transpiration conductance were formulated adaptable for various plant traits such as LAI or panicle's position. Figure 1 shows an example of the leaf area profile in heading stage normalized by total leaf area (LAI) and canopy height (h_c). Dots in Fig. 1 are the measured data of 'Akita-Komachi' cultivar to be described later in 2.2. The leaves canopy is dense in the middle- to upper- parts of the canopy in the late growing stage from flowering to maturity. The leaf area of i -th layer, $a(z)$ is calculated by

$$a(z) = \text{LAI} \int_{\Delta z_i} n\text{LAD}(z) dz \quad (1)$$

where LAI is the leaf area index, and Δz_i is the thick-

Fig. 1. Leaf area profile in heading stage normalized by total leaf area, LAI and canopy height, h_c in the IM²PACT. Dots are the measured data of 'Akita-Komachi' by clipping method in Tsukuba, 2005.

ness of the i -th layer. $nLAD(z)$ is the normalized leaf area profile shown in Fig. 1, and $\int_0^1 nLAD(z)dz = 1$, where z is the height from the ground surface normalized by canopy height (h_c).

The formulation of the leaf transpiration conductance (g_l) was also generalized,

$$g_l = g_{s0}(Q_p) f \quad (2)$$

where $g_{s0}(Q_p)$ is the maximum g_l (cm s^{-1}) without water stress formulated by the measured data in heading stage of 'Akita-Komachi' in Yoshimoto *et al.* (2005a). The f is a parameter for different varieties or growth stages, or a function of relative decline in g_{s0} due to dry air, which equals to unity in heading stage of 'Akita-Komachi' without stress. The $g_{s0}(Q_p)$ is assumed to be a rectangular hyperbolic function of PAR at each leaf layer, Q_p ($\mu\text{mol m}^{-2} \text{s}^{-1}$);

$$g_{s0}(Q_p) = \frac{g_{s\max} m_{is} Q_p}{g_{s\max} + m_{is} Q_p} \quad (3)$$

where the light-saturated stomatal conductance ($g_{s\max}$), the initial slope of the g_{s0} - Q_p curve at $Q_p=0$ (m_{is}), and Q_p are functions of normalized height, z ,

$$g_{s\max} = 1.47 z + 0.24 \quad (4)$$

$$m_{is} = 0.0026 z^{-1.011} \quad (5)$$

$$Q_p = Q_{p\text{top}} \exp \{-Ca_0(1-z)\} \quad (6)$$

$Q_{p\text{top}}$ is the Q_p above the canopy, a_0 is a mean leaf

Fig. 2. The generalized formulations of stomatal conductance at different leaf levels of 'Akita-Komachi' in heading stage without stresses in the IM²PACT.

area density ($=LAI/h_c$, $\text{m}^2 \text{m}^{-3}$) and C is a parameter showing the decrease in Q_p per unit leaf area density. Figure 2 shows a distribution of $g_{s0}(Q_p)$ at different leaf levels. Using these generalized formulations, the leaf transpiration resistance of the i -th layer (r_{si}) of the pathway of latent heat flux is written as:

$$r_{si} = \frac{1}{2g_{li}a(z)} \quad (7)$$

where the 2 in the denominator means the transpiration conductance from both sides of leaves.

Other resistances of each (i -th) layer such as the bulk aerodynamic resistance (r_{ha}), the aerodynamic resistance within the vegetation (r_{ai}) and the leaf surface resistance (r_{bi}) are written as (A.20), (A.21) and (A.22) of Appendix B in Yoshimoto *et al.* (2005a), respectively. Those resistances in each layer are simply combined according to Ohm's law to obtain the bulk transfer coefficients such as those of the sensible and latent heat fluxes (C_{hc} and C_{ec}) for the vegetation canopy, and those for the water surface (C_{Hg} and C_{Eg}) of two energy budget equations of double-source model (Eqs. (1), (2) and (7)–(10) in Yoshimoto *et al.*, 2005a). The bulk transfer coefficients are used for heat budget calculation under neutral atmospheric stability condition as initial values, and the cumulated coefficients are corrected by the thermal stability. After iteration for correcting by the thermal stability, the vegetation canopy temperature (T_c) and the water surface temperature (T_g) are determined as the solutions of two energy budget equations.

2.1.2 Air temperature and humidity inside the canopy

The air temperature and absolute humidity at the panicle's height are calculated from their interpolating among the bulk sources; vegetation canopy, water surface and the air above the canopy, whose bulk temperatures are already-known variables as solutions of double-source model (T_c , T_g), and the measured air temperature above the canopy (T_a), respectively. The interpolating among them is conducted by the cumulated resistances of the pathways of sensible and latent heat fluxes simply according to Ohm's law. The schematic illustration of the pathways is shown in Fig. 3. The panicle is assumed to be at z_p , the height normalized by h_c , which is generally less than unity (see Fig. 1). Geometrically, for the sensible heat transfer,

$$\frac{T_g - T_{ac}}{r_g} + \frac{T_c - T_{ac}}{r_c} = \frac{T_c - T_a}{r_a} \quad (8)$$

Fig. 3. Schematic diagram illustration of the path of sensible heat (a) and latent heat (b).

where T_{ac} is the air temperature at the panicle's height (z_p), r_g is the cumulated resistance to the sensible heat transfer from the water surface to the air at the panicle's height (z_p), r_c is that from the vegetation canopy, and r_a is that from the air above the canopy. Each cumulated resistance is obtained by combining all the resistance of each layer (r_{ha} , r_{ai} and r_{bi}) along the pathways in Fig. 3a. The formulation of r_{ha} , r_{ai} and r_{bi} is same as mentioned in 2.1.1. The T_{ac} is obtained by the transposition of Eq. (8) as

$$T_{ac} = \left(\frac{T_g}{r_g} + \frac{T_c}{r_c} + \frac{T_a}{r_a} \right) / \left(\frac{1}{r_g} + \frac{1}{r_c} + \frac{1}{r_a} \right) \quad (9)$$

The absolute humidity at the panicle's height (q_{ac}) can be calculated in the same way as T_{ac} , by replacing the bulk temperatures (T_c , T_g and T_a) with their absolute humidities ($q_{sat}(T_c)$, $q_{sat}(T_g)$ and q_a), and the cumulated resistances to the sensible heat transfer with those to the latent heat transfer.

$$q_{ac} = \left(\frac{q_{sat}(T_g)}{r_g} + \frac{q_{sat}(T_c)}{r_c} + \frac{q_a}{r_a} \right) / \left(\frac{1}{r_g} + \frac{1}{r_c} + \frac{1}{r_a} \right) \quad (10)$$

where $q_{sat}(T)$ is the saturated absolute humidity (g m^{-3}) at temperature T , and r_{ce} is the cumulated resistance to the latent heat transfer from the vegetation canopy to the air at the panicle's height (z_p), which is calculated using r_{si} , r_{ai} and r_{bi} (Fig. 3b).

As the bulk heat balance models lead a bulk temperature of the vegetation canopy instead of the leaf temperature profile, the air temperature (T_{ac})

calculated by Eq. (9), strictly saying, does not mean the air temperature at the panicle's height but a bulk air temperature as the most representative air temperature inside the canopy. We assume, however, the T_{ac} as the air temperature in the vicinity of panicle, standing between panicles and the air above the canopy, and solve the heat balance of panicle at the following panicle temperature sub-model. This assumption is adequate as a simplest approximation, because the panicles generally distribute at the layer with lots of leaves in the upper part of canopy, where the leaf temperature is close to the bulk temperature of vegetation canopy (T_c) which contributes to the sensible heat transfer mostly. Generally in the double-source model approaches, the T_{ac} inside the canopy calculated by such interpolation is equivalent to the 'aerodynamic surface temperature' (e.g., Lhomme and Monteny, 2000), which is the representative surface temperature for sensible heat flux of the canopy (Kondo and Watanabe, 1992; Brutsaert and Sugita, 1996; Campbell and Norman, 1998). Although there is an uncertainty in the bias between its representative surface and the actual panicle's height, the T_{ac} by Eq. (9) is still appropriate enough as a virtual but representative air temperature inside the canopy as the first step for this simple model which can be incorporated into the meteorology database. However, in case that the panicle distributed at lower canopy layer with sparse leaves, or at the top of canopy without coexisting leaves like spikes of wheat, this assumption causes the error on the estimation of the air temperature inside the canopy.

2.1.3 Panicle temperature sub-model

Panicle temperature (T_p) is calculated by the panicle temperature sub-model, which is a heat balance model between panicle and the air in the vicinity of panicle (based on Yoshimoto *et al.*, 2005b). The panicle is assumed to be at z_p , the height normalized by h_c as already shown in Fig. 1. The radiation input to panicle layer, R_{in} can be written as

$$R_{in} = F_p (1 - \alpha_p) (\sec Z \ p_{dir} + d_f \ p_{dif}) R_{sd} + F_p \ d_f (1 - \alpha_p) R_{su} + F_p \ d_f (L_d + L_u) \quad (11)$$

where R_{sd} and R_{su} are downward and upward short-wave radiations into the panicle layer, and L_d and L_u are those of longwave radiations. α_p and F_p are the reflection rate and inclination factor of the panicle. The α_p is set to 0.3, which is assumed the same as that of leaves. The F_p is set to 0.35 (Oue, 2003b). Z is the solar zenith angle, and d_f is the diffusivity factor for longwave radiation, which is set to 1.66 (=sec 53°) in this paper. p_{dir} and p_{dif} are the proportions of direct irradiance and diffused irradiance, respectively. The p_{dif} is set to 0.15, the typical daily value in clear sky using the empirical formulation by Liu and Jordan (1960), and the p_{dir} is set to 0.85 (=1- p_{dif}).

L_d and L_u can be written as

$$L_d = (1 - m_{L,upper}) \sigma T_c^4 + m_{L,upper} R_{l,top} \quad (12)$$

$$L_u = (1 - m_{L,lower}) \sigma T_c^4 + m_{L,lower} \sigma T_g^4 \quad (13)$$

where $R_{l,top}$ is the downward longwave radiation at above the canopy ($W \ m^{-2}$), σ is the Stefan-Boltzmann constant ($=5.67 \times 10^{-8} \ W \ m^{-2} \ K^{-4}$), and $m_{L,upper}$ and $m_{L,lower}$ are the transmittances for longwave radiation of the vegetation canopy over and below the panicle's height (z_p), respectively, which are calculated as:

$$m_{L,upper} = \exp(-F a_{upper} d_f) \quad (14)$$

$$m_{L,lower} = \exp(-F a_{lower} d_f) \quad (15)$$

where F is the inclination factor of the leaves, and a_{upper} and a_{lower} are the leaf area index of leaves over and below the panicle's height (z_p), respectively, which are calculated using Eq. (1) as:

$$a_{upper} = LAI \int_{z_p}^1 nLAD(z) dz \quad (16)$$

$$a_{lower} = LAI \int_0^{z_p} nLAD(z) dz \quad (17)$$

R_{sd} and R_{su} are assumed to change in proportional to

the downward solar radiation at above the canopy, $R_{s,top}$, for the simple structure of this model adaptable for various plant traits as:

$$R_{sd} = R_{s,top} \exp\{-Ca_0(1 - z_p)\} \quad (18)$$

$$R_{su} = \alpha_{sl} R_{s,top} \quad (19)$$

The proportionality coefficient of R_{su} , α_{sl} corresponds to the albedo of water surface and leaves below the panicle layer, which is assumed to be described from the general solutions of two-stream model (e.g., Kawakata, 2005) and written by

$$\alpha_{sl} = \frac{-(p - \alpha_s) e^{-\lambda \cdot LAI}}{(1 - \alpha_s p) e^{\lambda \cdot LAI} + (\alpha_s - p) p e^{-\lambda \cdot LAI}} e^{\lambda \cdot a_{upper}} + \frac{-(1 - \alpha_s p) p e^{\lambda \cdot LAI}}{(1 - \alpha_s p) e^{\lambda \cdot LAI} + (\alpha_s - p) p e^{-\lambda \cdot LAI}} e^{-\lambda \cdot a_{upper}} \quad (20)$$

where α_s is the albedo of the water surface, which is set to 0.05, and p and λ are written by

$$p = \frac{1 - \sqrt{1 - \alpha_i^2}}{\alpha_i} \quad (21)$$

$$\lambda = \frac{1 - p^2}{1 + p^2} F \quad (22)$$

where α_i is the reflection rate of leaves, which is set to 0.3, the typical value of single leaves of crop species (Jones, 1984).

R_{in} in Eq. (11) should balance with heat fluxes in the panicle layer,

$$R_{in} = H_p + IE_p + 2F_p d_f \sigma T_p^4 \quad (23)$$

where H_p and IE_p are the sensible and latent heat fluxes for panicles, which are written as follows:

$$H_p = g_h \rho c_p (T_p - T_{ac}) \quad (24)$$

$$IE_p = g_e l \{q_{sat}(T_p) - q_{ac}\} \quad (25)$$

where ρ and c_p are the density ($g \ m^{-3}$) and specific heat ($J \ g^{-1} \ K^{-1}$) of the air, respectively. l is the specific latent heat of vaporization ($J \ g^{-1}$). The g_h and g_e are the conductances for sensible and latent heat transfer between panicle and the air in the vicinity of panicle, which are calculated as below,

$$g_h = c_h u(z_p) \quad (26)$$

Fig. 4. Relationship between panicle transpiration conductance, g_p of ‘Akita-Komachi’ and the relative humidity in the vicinity of panicle, RH_{ac} during flowering stage in the ambient CO_2 and high CO_2 plots in Shizukuishi FACE experiment. The panicle’s height was 0.65 m, and the canopy height, h_c was 0.8 m from the ground in both plots, which leads that the z_p for RH_{ac} measurement was 0.81.

$$g_c = \frac{g_h g_p}{g_h + g_p} \quad (27)$$

where g_p is the panicle transpiration conductance ($m s^{-1}$), c_h is the bulk transfer coefficient of an individual vegetation element for sensible heat, and $u(z_p)$ is the wind speed ($m s^{-1}$) at the panicle’s position, z_p . The $u(z_p)$ is calculated by equations (A.23)–(A.27) of Appendix B in Yoshimoto *et al.* (2005a)

The third term in right side of Eq. (23) is the longwave radiation from panicle to both over and below the panicle layers. The panicle temperature, T_p is calculated by solving equations (11)–(27).

2.1.4 Panicle transpiration conductance

In order to model the panicle transpiration conductance (g_p), we used a g_p dataset obtained at the rice paddy of FACE (Free-Air CO_2 Enrichment) experiment in Shizukuishi, Japan ($39^{\circ}40'N$, $141^{\circ}00'E$) in 2004, where ‘Akita-Komachi’ cultivar was grown. The details of the field layout and cultivation in FACE experiment were the same as described in Okada *et al.* (2001) and Kim *et al.* (2001). In both the high CO_2 and ambient CO_2 plots, the g_p at flowering stage was measured by a steady-state porometer (LI-1600; Li-Cor, U.S.A.) attached with a cylindrical chamber for irregular shaped leaves (1600-07; Li-Cor, U.S.A.).

The g_p data of wet panicles by rain were excluded, because they showed generally large and ‘ad hoc’ values depending on the degree and position of

wetting. Figure 4 shows the relationship between g_p and the relative humidity in the vicinity of panicle (RH_{ac}) during flowering stage in the both CO_2 plots, where the panicle’s height was 0.65 m, and the canopy height, h_c was 0.8 m from the ground in both plots, which leads that the normalized panicle height (z_p) for RH_{ac} measurement was 0.81. The g_p changed diurnally in close association with RH_{ac} , whereas the change in leaf stomatal conductance (g_{so}) is generally closely linked with light intensity (e.g., as Fig. 2). There are no stomata on the surface of the panicle, and g_p seemed to be determined by its water balance under the humidity environmental variation. As there was no clear difference in g_p between the high CO_2 and ambient CO_2 plots, the g_p of ‘Akita-Komachi’ at flowering stage was formulated using the both CO_2 plots data altogether as

$$g_p = 0.0055 \exp(0.052 RH_{ac}) \quad (28)$$

This relationship between the g_p and RH_{ac} was held for 2–3 days after flowering for ‘Akita-Komachi’ in the current Shizukuishi dataset. It is noted, however, that Yoshimoto *et al.* (2005b) showed the rapid decrease of the g_p in the first 2 days after flowering. The reason of this contradiction might be attributed to the cultivar difference, which is ‘Wuxiangjing 14’ in Yoshimoto *et al.* (2005b). The g_p difference between cultivars should be examined and determined in order for applying the model to various cultivars in a future study.

2.2 Measurement

In order to validate the IM²PACT, we conducted an environmental manipulation experiment in 2005 at rice paddy field of National Institute for Agro-Environmental Sciences, Japan ($36^{\circ}01'N$, $140^{\circ}06'E$). Two rice varieties (*Oryza sativa* L.; ‘Akita-Komachi’ and ‘Hatsu-Boshi’) were grown at five bays of rice paddy; each bay is surrounded by concrete frame and has 4×10 m area. Plants were sown on 16 May, and transplanted on 6 June with one seedling planting. The cultivation density was 30×15 cm and they were fertilized as $N:P_2O_5:K_2O=8, 4, 4$ ($g m^{-2}$). Two treatment plots were provided in each bay; one is the control (C), and another is the retarding of leaf transpiration (RT). Two varieties and two treatments were arranged in each bay with randomized block design, which provided five replicates. The area of one treatment plot including two varieties was 4×5 m, half of the bay. We observed the thermal distribution of canopy surface in these plots by thermal image from

the sky, and ascertained that each treatment plot was large enough to keep the micrometeorology inside the canopy homogeneous without the effect by edges. Two rice varieties were cultivated in the RT experiment, however in this paper, the results for 'Akita-Komachi' are shown, as the g_p model described as Eq. (28) and Fig. 4 is for 'Akita-Komachi' at flowering stage.

In both varieties, the fully panicle emergence was August 6 to 7. The leaf area profile of 'Akita-Komachi' was measured by clipping method on August 8, whose data are shown in Fig. 1. The canopy height (h_c) was averagely 0.95 m, and their profiles were almost analogous when normalized by h_c . The position of flowering panicle was about 0.75 m from the ground, which leads that the normalized panicle height (z_p) is 0.79. The z_p was almost the same as Shizukuishi FACE experiment (see 2.1.4), in spite of the h_c difference between both experiments.

The leaf transpiration retardant of wax-type water dispersible powder (Greener; Jatto Co. Ltd., Japan) had been sprayed on leaves in the RT treatment plots on August 3, just before panicle emergence. During their flowering stage, we measured the air temperature and humidity at the position of flowering panicle at

both treatment plots of 'Akita-Komachi' canopy in one replicate, and above the canopy at the centre of one replicate. We used temperature and humidity sensor probes (HMP36ASPF; for panicle's position, and HMP45D; for above the canopy, Vaisala, Finland) with handmade ventilation fans. The air intakes to the sensors were set at the height of flowering panicles for inside the canopy (0.75 m from the ground, $z_p=0.79$), and at 1.5 m above the ground for above the canopy. The temperatures of leaves and panicles were measured by very thin thermocouples (copper-constantan, 0.08 mm diameter) in both treatment plots. The thermocouples were put on the surfaces of nine flowering panicles and seven flag leaves at the same height as the flowering panicles per one plot using quick-drying adhesive so that the direction of the measured surface was not biased. The thermocouples were very thin and their contact area onto plant bodies was very small, and it was ascertained by taking thermal image that the attachment of thermocouples did not affect the leaf and panicle temperatures.

At 1.3 m above the ground, we measured downward solar radiation ($R_{s\ top}$) with a pyranometer (MS-800; EKO Co., Japan) and downward longwave radiation ($R_{l\ top}$) with a pyrgeometer (Model PIR; Eppley Laboratory Inc., U.S.A.). Wind speed was measured with a sonic anemometer (Model 8352; G. Lufft, Germany) at 1.5 m above the ground. All data were sampled every 10 s, averaged over 10 min, and recorded by dataloggers (CR10X; Campbell Scientific Inc., U.S.A.).

In order to check the effect of transpiration retardant on leaf transpiration, leaf transpiration conductance of flag leaves was measured by a steady-state porometer (LI-1600; Li-Cor, U.S.A.) in both varieties and both treatment plots.

3. Results and Discussions

3.1 Model validation by transpiration retarding experiment

Table 1 shows the leaf transpiration conductance of 'Akita-Komachi' cultivar measured in both plots of the control (C) and the retarding of leaf transpiration (RT). There was a heavy rain on August 8 to be mentioned later (Fig. 5), however, the leaf transpiration retarding effect continued in days after rain, because the leaf transpiration retardant is wax-type and remained on the leaf surface once it dried after initially sprayed. Although the standard error of the conductance in RT plot tended to be larger than in C plot, the transpiration

Table 1. Leaf transpiration conductance of 'Akita-Komachi', g_l (cm s^{-1}) and the PAR, Q_p ($\mu\text{mol m}^{-2} \text{s}^{-1}$), at the control (C) and the transpiration retarding (RT) treatment plots measured by porometer from August 4 to 11, 2005.

Date	g_l (cm s^{-1})		Q_p ($\mu\text{mol m}^{-2} \text{s}^{-1}$)		p-value from a t-test	g_l ratio RT/C
	C	RT	C	RT		
8/4	0.83	0.46	1288	1178	0.0005	0.56
	(0.027)	(0.058)	(105)	(119)		
8/7	0.54	0.27	603	735	0.0019	0.50
	(0.010)	(0.059)	(67)	(57)		
8/8	0.77	0.49	1218	1109	0.1692	0.64
	(0.026)	(0.130)	(142)	(208)		
8/10	0.57	0.31	733	720	0.0053	0.53
	(0.029)	(0.064)	(53)	(195)		
8/11	0.72	0.45	1096	1039	0.0100	0.63
	(0.056)	(0.058)	(143)	(114)		

The g_l and Q_p values show the mean of five replicates and the values inside the parenthesis show their S.E., where three flag leaves were measured per one replicate and averaged in each replicate. T-test was conducted for five mean values of replicates ($n=5$).

Fig. 5. Diurnal variations of panicle temperature and micrometeorology inside the canopy at the control (C) plot with weather components as input data. (a) Solar radiation and wind speed, (b) the air temperature, T_a and relative humidity, RH above the canopy, (c) the precipitation, (d) the air temperature, T_{ac} and relative humidity, RH_{ac} inside the canopy, (e) the temperatures of panicle, T_p and vegetation canopy, T_c , and (f) the difference between the T_p and the air temperature above canopy, $T_p - T_a$, where dots mean the measured values, and lines the estimated by the IM²PACT.

Fig. 6. Diurnal variations of the effect of retarding of leaf transpiration on (a) the leaf, $dT_c (=T_c(RT)-T_c(C))$ and panicle, $dT_p (=T_p(RT)-T_p(C))$ temperatures, (b) the air temperature, $dT_{ac} (=T_{ac}(RT)-T_{ac}(C))$ and relative humidity, $dRH_{ac} (=RH_{ac}(RT)-RH_{ac}(C))$ and (c) the absolute humidity, $dq_{ac} (=q_{ac}(RT)-q_{ac}(C))$ inside the canopy. Dots mean the measured values, and lines the estimated by the IM²PACT.

conductance in RT was significantly reduced. As the reduction rate of the conductance by RT averaged through the flowering period was 0.57, we assumed the factor f in Eq. (2) as 1 and 0.57 in C and RT plot, respectively.

The IM²PACT was applied to the RT experiment. The meteorology data such as the air temperature (T_a) and relative humidity (RH) measured above the canopy, solar radiation, downward longwave radiation and wind speed were used as input data of the IM²PACT. The output data such as the air temperature (T_{ac}) and relative humidity (RH_{ac}) at panicle's height were compared with the measurement by temperature and humidity sensor probe at panicle's height. And the panicle temperature (T_p) and the bulk vegetation canopy temperature (T_c) were compared with the measurement by thermocouples on panicles and flag leaves at the same height of panicles, respectively.

Figure 5 shows the simulated results in C plot, where the panicle temperature (T_p) data are not shown after rain in 15:00 of August 8 until the panicles surface dried the next morning, as the g_p model is valid only for

panicles which are not wet by rain. The T_{ac} calculated by the IM²PACT tended to be higher than the measured T_{ac} in daytime, and the calculated RH_{ac} , lower than measured RH_{ac} (Fig. 5d). As mentioned in 2.1.2, the T_{ac} and RH_{ac} by the IM²PACT are the virtual values of T_{ac} and RH_{ac} inside the canopy, which means that they are not necessarily coincide with the real values of T_{ac} and RH_{ac} in the vicinity of the panicle. Their bias is one of the uncertainties of this model, however, the IM²PACT represent to a certain extent the T_{ac} and RH_{ac} in conjunction with the canopy heat balance, especially with the vegetation canopy temperature (T_c). It is adventitious that the bias was pretty small in the case that the panicles at flowering generally distribute at the layer with lots of leaves in upper part of canopy. The calculated T_c agreed with the measured T_c (Fig. 5e) due to the same reason.

The IM²PACT well simulated the panicle temperature (T_p) (Fig. 5e) in the flowering stage under daily variation of weather conditions (Figs. 5ab). The T_p in daytime was higher than T_c (Fig. 5e) by around 1°C in maximum. The T_p in daytime was higher than the

air temperature above the canopy (T_a) (Fig. 5f). Their difference ($T_p - T_a$) in daytime was larger on August 9 when the relative humidity (RH) was higher, than that on August 8 with lower RH . It is because that the drier air enhanced the panicle transpiration, which decreased the panicle temperature. Under the similar T_a and RH conditions in daytime on August 7 and 8, the ($T_p - T_a$) was larger on August 7, when the solar radiation was higher than on August 8.

Figure 6 shows the effect of leaf transpiration retarding (RT) on temperatures and humidity of the canopy. The vegetation canopy temperature elevated in daytime because the evaporation cooling decreased by RT. The increase in the vegetation canopy temperature (dT_c) by RT was estimated 1.1 to 1.3°C in daily maximum by the IM²PACT (Fig. 6a). The T_c increase caused the elevation of the air temperature (dT_{ac}) by 0.6 to 0.8°C in daily maximum, and the decrease of relative humidity (dRH_{ac}) by 4 to 5% in daily minimum inside the canopy (Fig. 6b). Due to RT, the absolute humidity inside the canopy (q_{ac}) decreased (Fig. 6c) as well as the RH_{ac} , which includes the apparent decrease by the T_{ac} increase. The model estimated values of dT_{ac} and dRH_{ac} are consistent with their measured values. The increase in the panicle temperature (dT_p) was calculated 0.6 to 0.8°C in daily maximum by RT (Fig. 6a). The measured values of dT_c ($=T_c(RT) - T_c(C)$) and dT_p ($=T_p(RT) - T_p(C)$) included scattering in daytime, because the exposure to the sun of the measured surfaces of leaves and panicles fluctuated depending on the environmental condition as solar direction, wind and the canopy geometry, and subtraction of two measured values were originally too small to be apart from the environmental fluctuation. However, their measured and estimated values had the same levels and the same tendency; that is, both of dT_c and dT_p have large positive values in daytime and the magnitude of dT_p in daytime was smaller than dT_c .

The IM²PACT was validated by the RT experiment and was proved to simulate not only the panicle temperature under various weather conditions but also the effects on panicle temperature of leaf transpiration characteristics via changes in micrometeorology inside the canopy.

3.2 Panicle temperature in the record hot summer of 2007

As a measure of heat induced spikelet sterility (HISS) of rice, the daily maximum air temperature is commonly used because it is considered to be the most

related variable to HISS among generally available meteorological variables which are easy to obtain. It is, however, ideal to use temperature of panicle which is the organ susceptible to the HISS.

In the summer of 2007, the Kanto and Tokai regions of Japan experienced extremely high temperature; for example, the daily maximum air temperature of 40.9°C was recorded in mid-August in Kumagaya of Saitama Prefecture in Kanto region and in Tajimi of Gifu Prefecture in Tokai region, which is far higher than the air temperature threshold of HISS according to various chamber experiments. Hasegawa *et al.* (2011) examined the HISS of panicle samples from paddy fields located in Kanto and Tokai regions in 2007 and 2008. The rate of HISS in the hot summer of 2007 was higher than in the normal summer of 2008, and crops whose heading and flowering coincided with the heat wave in mid-August had a higher rate of sterility than crops that flowered earlier or later. The rates of HISS, however, were lower than those indicated by chamber experiments. One possible explanation is that the temperature of flowering panicle as the organ actually susceptible to the HISS can differ from the daily maximum air temperature.

In order to examine the gap between the temperatures, we estimated the panicle temperature distribution from July to September in 2007 in the central Japan including Kanto and Tokai regions, by applying the IM²PACT to meteorological dataset arranged based on ANEMOS by Japan Weather Association.

ANEMOS (Area-oriented Numerical prediction and Environmental assessment MODELing System) is an area-oriented meteorology model, which was applied for providing a 5 km-grid point dataset of hourly surface meteorology data (the air temperature, solar radiation, wind speed and relative humidity) from a 20 km GPV (Grid Point Value) numerical prediction dataset by Japan Meteorological Agency. A 1 km-grid point dataset was calculated by interpolating of the 5 km-grid point dataset, where the bias originated by ANEMOS in the air temperature and solar radiation was corrected by using data in AMeDAS (Automated Meteorological Data Acquisition System) points and 67 meteorological stations, respectively. As ANEMOS provided the wind speed at 10 m from the ground, the wind speed at 1.5 m from the ground for input to the IM²PACT was corrected by fitting logarithmic curve with height and roughness length of rice paddy field using Kuwagata and Kondo (1990; 1991). The

downward longwave radiation was calculated by Kondo *et al.* (1991) using the air temperature, solar radiation, relative humidity and the surface air pressure corrected by altitude of respective grid point. Thus, a 1 km-grid point dataset of hourly meteorology was used to the IM²PACT as input variables; T_a , RH , $R_{s\ top}$, $R_{l\ top}$ and wind speed at 1.5 m. The plant traits in the IM²PACT such as the leaf transpiration conductance, the panicle

transpiration conductance and LAI were set to the same among all grid points, in order to focus on the effects of meteorological differences among areas on the gap.

Figure 7 shows the distributions of the daily maximum air temperature, $T_{a\ max}$ and the panicle temperature, T_p at flowering hours (10:00-12:00 for typical rice varieties in Japan) on the extremely hot

Fig. 7. Distributions of (a) the daily maximum air temperature, $T_{a\ max}$ and (b) the panicle temperature, T_p , averaged for flowering hours (10:00-12:00), on August 16, 2007. The T_p was estimated by the IM²PACT.

Fig. 8. Distribution of the difference between the panicle temperature and the air temperature, $T_p - T_a$, averaged for flowering hours (10:00-12:00) on August 16, 2007. The T_p was estimated by the IM²PACT.

Fig. 9. Distribution of the relative humidity, RH , averaged for flowering hours (10:00-12:00), on August 16, 2007.

day, August 16. The model calculation interval was 1 hour along the ANEMOS dataset and the calculated T_p was averaged over 10:00, 11:00 and 12:00 for flowering hours. The spatial distribution of the estimated T_p did not necessarily coincide with the $T_{a \max}$ distribution. The daily maximum temperature was remarkably high in the inland areas of Kanto and Tokai regions compared to other regions, where $T_{a \max}$ reached around 40°C. However, the T_p at flowering hours in the inland areas of Kanto and Tokai regions was not so high compared to other regions; for example, 34.6°C in Kumagaya and 35.7°C in Tajimi. This is because, in addition to the air temperature during flowering hours (10:00-12:00) being lower than the daily maximum temperature generally recorded in the early afternoon, other meteorological factors such as solar radiation, wind speed and humidity also affect the panicle temperature.

Figure 8 shows the temperature difference between the panicle and the air at flowering hours (10:00-12:00). The panicle temperature, T_p was lower than the air temperature, T_a at flowering hours in inland area of Kanto region, while in other regions T_p was the same or higher than T_a . The difference of temperatures between the panicle and the air ($T_p - T_a$) at flowering hours was widely ranged from -2 to +3°C even only in Kanto region. One main reason of this is the humidity difference among areas (Fig. 9). The drier air less than 50% in inland area of Kanto region caused the evaporation cooling of canopy and panicle, resulting in the lower T_p than the air temperature at flowering hours. While in coastal area of the western Kanto region, the relative humidity was higher, ranged 60 to 70%, resulting in the T_p being higher than the air temperature at flowering hours (Fig. 8) and even higher than $T_{a \max}$ (Figs. 7ab).

The IM²PACT estimation with ANEMOS data showed that there is a great gap in spatial distributions between the daily maximum air temperature and the panicle temperature at flowering, because the difference of meteorology, especially relative humidity, among areas altered the relationship between the panicle and the air temperatures at flowering hours, as well as that the flowering hours are generally different from the time of daily maximum temperature. This strongly suggests that we must use the panicle temperature instead of the air temperature in the daily maximum, as a measure variable for HISS.

Many chamber and field experiments addressed to

the rice HISS issues have been conducted and plenty of crop yield data have been accumulated not only at prefectures in Japan but also at various climate zones in the world. Those data can be analysed on an equal footing with each other, by filling the gap between the organ temperature and the measured air temperature, with mediation using the IM²PACT. As the IM²PACT can also simulate the elevated CO₂ effect on panicle temperature and canopy micrometeorology via stomatal closure as shown by RT experiment in substitution for it, it is expected to contribute for the projection of heat stress under climate change. The IM²PACT has an advantage of simplicity due to being bulk energy balance model, which includes, on the contrary a disadvantage that it cannot simulate the exact profiles of temperature and humidity of the canopy because it simulates as ‘bulk’. In case that, for example, it refers to the effect of panicle height difference on the panicle temperature depending on various rice genotypes in climate change adaptation study, the multi-layer structure must be taken into the model in the future. The IM²PACT is, however, still a powerful tool to elucidate the panicle temperatures in the climate change impact study as the first step, and to bridge between the responses of crop susceptible to heat and the meteorological data of present and future predicted under climate change. The IM²PACT is installed in the model-coupled agro-meteorological database, called MeteoCrop (Kuwagata *et al.*, 2011) in order to estimate the panicle temperatures at flowering stage in surface meteorological stations (156 sites). It is expected that the use of such database combined with field surveys of heat stress in farmers’ field contributes to improve the precision of HISS models for climate change impact study.

4. Conclusions

In order to cope with uncertainties caused by the gap of thermal environment between the air and the panicle as the organ susceptible to heat, we developed a micrometeorology model focusing canopy and panicle temperatures; IM²PACT (Integrated Micrometeorology Model for Panicle And Canopy Temperature). The IM²PACT was validated by leaf transpiration retarding (RT) experiment. During their flowering stage, leaf temperature elevated by RT treatment, which caused warming and drying of the air in the canopy, resulting in the elevation of the panicle temperature. The IM²PACT well simulated the RT experiment, and was

proved to simulate not only the panicle temperature magnitude but also the effects on panicle temperature of leaf transpiration characteristics via changes in micrometeorology inside the canopy.

The IM²PACT was applied to the weather dataset based on ANEMOS in order to analyse the panicle temperature at Kanto and Tokai regions of extremely hot summer in 2007. There was a great gap in spatial distributions between the panicle temperature and the daily maximum air temperature which is commonly used as a measure of HISS. It is because the difference of meteorology, especially relative humidity, among areas altered the panicle-air temperature difference, as well as that the flowering hours are generally different from the time of daily maximum temperature. This strongly suggests that we must refer to the panicle temperature instead of the air temperature in daily maximum, as a measure variable for HISS. The IM²PACT is a powerful tool to elucidate the panicle temperatures in the climate change impact study, and to bridge between the responses of crop susceptible to heat and the meteorological data of present and future predicted under climate change.

Acknowledgments

This study was supported partly by the Ministry of Agriculture, Forestry and Fisheries of Japan project, “Development of mitigation and adaptation techniques to global warming in the sectors of agriculture, forestry, and fisheries”. The 1 km-grid point dataset based on ANEMOS was provided by Japan Weather Association.

References

- Angus, J., 1997: Rice production. A book review on ‘Modeling the Impact of Climate Change on Rice Production in Asia’. *Field Crops Res.*, **52**, 286–287.
- Brutsaert, W., and Sugita, M., 1996: Sensible heat transfer parameterization for surfaces with anisothermal dense vegetation. *J. Atmos. Sci.*, **53**, 209–216.
- Campbell, G. S., and Norman, J. M., 1998: *An Introduction to Environmental Biophysics (2nd Edition)*. Springer-Verlag, U.S.A., 307 pp.
- Carriger, S., and Vallee, D., 2007: More crop per drop. *Rice Today*, **6**(2), 10–13.
- Hasegawa, T., Ishimaru, T., Kondo, M., Kuwagata, T., Yoshimoto, M., and Fukuoka, M., 2011: Spikelet sterility of rice observed in the record hot summer of 2007 and the factors associated with its variation. *J. Agric. Meteorol.*, **67**, 225–232.
- IPCC, 2007a: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L.). Cambridge University Press, Cambridge, UK, 996 pp.
- IPCC, 2007b: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J., and Hanson, C. E.). Cambridge University Press, Cambridge, UK, 976 pp.
- Jones, H. G., 1992: *Plants and Microclimate (2nd Edition)*. Cambridge University Press, Cambridge, UK, 428 pp.
- Kawakata, T., 2005: Application of two-stream model to solar radiation of rice canopy. *J. Agric. Meteorol.*, **61**, 123–129 (in Japanese with English summary).
- Kim, H. Y., Horie, T., Nakagawa, H., and Wada, K., 1996: Effect of elevated CO₂ and high temperature on growth and yield of rice. II. The effect on yield and its components of Akihikari rice. *Jpn. J. Crop Sci.*, **65**, 644–651 (in Japanese with English summary).
- Kim, H. Y., Loeffering, M., Miura, S., Kobayashi, K., and Okada, M., 2001: Growth and nitrogen uptake of CO₂-enriched rice under field conditions. *New Phytol.*, **150**, 223–229.
- Kondo, J., Nakamura, T., and Yamazaki, T., 1991: Estimation of the solar radiation and downward atmospheric radiation. *Tenki*, **38**, 41–48 (in Japanese).
- Kondo, J., and Watanabe, T., 1992: Studies on the bulk transfer coefficients over a vegetated surface with a multilayer energy budget model. *J. Atmos. Sci.*, **49**, 2183–2199.
- Kuwagata, T., and Kondo, J., 1990: Estimation of aerodynamic roughness at the regional meteorological station (AMeDAS) in the central part of Japan. *Tenki*, **37**, 197–201 (in Japanese).
- Kuwagata, T., and Kondo, J., 1991: Estimation of aerodynamic roughness at the regional meteorological station (AMeDAS) in western Japan. *Tenki*, **38**, 491–494 (in Japanese).
- Kuwagata, T., Yoshimoto, M., Ishigooka, Y., Hasegawa, T., Utsumi, M., Nishimori, M., Masaki, Y., and Saito, O., 2011: MeteoCrop DB: an agro-meteorological

- database coupled with crop models for studying climate change impacts on rice in Japan. *J. Agric. Meteorol.*, **67**, 297–306.
- Lhomme, J. P., and Monteny, B., 2000: Theoretical relationship between stomatal resistance and surface temperatures in sparse vegetation. *Agric. For. Meteorol.*, **104**, 119–131.
- Liu, B. Y., and Jordan, R. C., 1960: The interrelationship and characteristic distribution of direct, diffuse, and total solar radiation. *Solar Energy*, **4**, 1–19.
- Matsui, T., Kobayashi, K., Yoshimoto, M., and Hasegawa, T., 2007: Stability of rice pollination in the field under hot and dry conditions in the Riverina region of New South Wales, Australia. *Plant Prod. Sci.*, **10**, 57–63.
- Matsui, T., Omasa, T., and Horie, T., 1997: High temperature-induced spikelet sterility of japonica rice at flowering in relation to air temperature, humidity and wind velocity. *Jpn. J. Crop Sci.*, **66**, 449–455.
- Nishiyama, I., 1981: Temperature inside the Flower of Rice Plants. *Jpn. J. Crop Sci.*, **50**, 54–58.
- Okada, M., Lieffering, M., Nakamura, H., Yoshimoto, M., Kim, H. Y., and Kobayashi, K., 2001: Free-air CO₂ enrichment (FACE) using pure CO₂ injection: system description. *New Phytol.*, **150**, 251–260.
- Oue, H., 2003a: Evapotranspiration, Photosynthesis and Water Use Efficiency in a Paddy Field (I) —Stomatal Conductance Model and Single Leaf Photosynthesis Model of Rice. *J. Jpn. Soc. Hydrol. Water Resour.*, **16**, 375–388 (in Japanese with English summary).
- Oue, H., 2003b: Evapotranspiration, Photosynthesis and Water Use Efficiency in a Paddy Field (II)—Prediction of energy balance and water use efficiency by numerical simulations based on a multilayer model. *J. Jpn. Soc. Hydrol. Water Resour.*, **16**, 389–407 (in Japanese with English summary).
- Oue, H., Yoshimoto, M., and Kobayashi, K., 2005: Effects of free-air CO₂ enrichment on leaf and panicle temperatures of rice at heading and flowering stage. *Phyton*, **45**, 117–124.
- Satake, T., and Yoshida, S., 1978: High temperature-induced sterility in indica rices at flowering. *Jpn. J. Crop Sci.*, **47**, 6–17.
- Sheehy, J. E., Mitchell, P. L., Beerling, D. J., Tsukaguchi, T., and Woodward, F. I., 1998: Temperature of rice spikelets: thermal damage and the concept of a thermal burden. *Agronomie*, **18**, 449–460.
- Wang, C., Yang, J., Wa, J., and Cai, Q., 2004: Influence of high and low temperature stress on fertility and yield of rice (*Oryza sativa* L.): Case study with the Yangtze River rice cropping region in China. *Abstracts, World Rice Research Conference 2004*, 97.
- Watanabe, T., 1994: Bulk parameterization for a vegetated surface and its application to a simulation of nocturnal drainage flow. *Boundary-Layer Meteorol.*, **70**, 13–35.
- Yoshimoto, M., Oue, H., and Kobayashi, K., 2005a: Energy balance and water use efficiency of rice canopies under free-air CO₂ enrichment. *Agric. For. Meteorol.*, **133**, 226–246.
- Yoshimoto, M., Oue, H., Takahashi, H., and Kobayashi, K., 2005b: The effects of FACE (Free-Air CO₂ Enrichment) on temperatures and transpiration of rice panicles at flowering stage. *J. Agric. Meteorol.*, **60**, 597–600.