

MINCERnet: Multi-site Monitoring Network of Heat Stresses and Micrometeorology in Rice Paddies under Various Climates

Mayumi Yoshimoto, Minehiko Fukuoka and Toshihiro Hasegawa

*National Institute for Agro-Environmental Sciences
Kannondai 3-1-3, Tsukuba, Japan*

Abstract

Rice yield may be reduced substantially when the crop is exposed to the excessive heat predicted under future climate conditions, but the magnitudes of the yield losses under open-field conditions are difficult to predict. One reason for this difficulty is the micrometeorological ‘gap’ between the air above and within the plant canopy, the magnitude of which can differ greatly depending on environmental factors. To better understand the occurrence of heat stress under field conditions, we need to accurately measure the thermal environment within the canopy. However, most commercially available meteorological instrument packages are not well designed for use within a rice canopy, and special knowledge is required for their installation. Another problem is the supply of power to the equipment, because electricity is rarely available in a rice paddy. To overcome these difficulties, we developed MINCER (Micrometeorological Instrument for the Near-Canopy Environment of Rice), a radiation-shielded, solar-powered, force-ventilated system that is designed to facilitate its use by researchers. Then, we established a network based on MINCER, called MINCERnet, for monitoring the thermal environment within the rice canopy in paddy fields and for collecting other crop data. The network initially included sites in eight of the world’s rice growing regions. Preliminary results showed that the difference in air temperature (T_a) between the air within the canopy and that above the canopy varied depending on relative humidity. In addition, T_a at the weather station nearest to each respective field was higher than T_a above the rice canopy. T_a within the canopy near the panicles was lower than T_a above the canopy, but the magnitude of the difference varied among sites, because the degree to which the canopy was cooled by evapotranspiration depended on characteristics of the ambient environment and the plant canopy. By recording data from different climate zones, MINCERnet will improve our quantitative understanding of the impacts of climate change on rice cultivation.

Keywords: air temperature, climate change, heat stress, micrometeorology, monitoring network, relative humidity, rice canopy

1. Introduction

According to the 5th assessment report of the Intergovernmental Panel on Climate Change, it is virtually certain that as global mean temperature increases, hot temperature extremes will

occur more frequently over most land areas, and heat waves of long duration are likely to occur with high frequency (IPCC, 2013). Excessive heat, even of short duration, can adversely affect reproductive growth and thereby reduce crop yields. However, because the effects of extreme heat events on crop growth and yield have not been well accounted for by crop models, we cannot yet properly predict the negative effects of rising temperature. One of the major uncertainties in future yield predictions thus involves the effects of extreme heat (Yoshimoto et al., 2010).

Although rice is well adapted to a range of environments, growth-chamber experiments have shown that rice is highly susceptible to heat (Satake and Yoshida, 1978; Kim et al., 1996). Flowering is the most sensitive stage, and heat-induced spikelet sterility (HISS) is the major cause of yield losses. The threshold temperature for HISS at the time of flowering is around 35°C, and temperatures this high already occur sometimes under the current climate. The rice yield loss due to HISS, however, has not been well documented by open-field studies. Filling the knowledge gap between growth-chamber and open-field studies is therefore an important task for crop physiology and agricultural meteorology researchers.

Thermal conditions in the rice canopy can differ from the ambient air temperature in unpredictable ways. For instance, Matsui et al. (2014) have demonstrated that panicle temperatures can be substantially (as much as 6 to 7°C) lower than the air temperature under hot and dry conditions in the Riverina region of New South Wales, a major rice production area in Australia; in contrast, a temperature difference between the panicles and the ambient air of only around 0.5°C has been reported in China's humid Jiangsu Province (Yoshimoto et al., 2005). This regional difference suggests that the impacts of rising temperatures can be substantially moderated by factors that affect the canopy's heat balance.

The temperature difference between the ambient air (above the canopy) and the air within the rice canopy depends on meteorological conditions, such as solar radiation intensity, wind speed, and relative humidity, and on field hydrological conditions. Other important factors that influence canopy and panicle thermal conditions include the physiological and morphological properties of the rice variety. To properly assess the vulnerability of rice production to environmental changes, we need better micrometeorological data from open paddy fields under variable climate and management conditions. Unfortunately, limited information is available on the relationship between canopy and ambient air temperatures, which limits our ability to assess the risks of heat damage from excessive heat.

For this reason, we initiated a research project to develop a network of monitoring sites in rice paddies for recording micrometeorological conditions and crop data for use in assessing heat damage. We developed a simple system for monitoring air temperature and relative humidity profiles within the rice canopy that can be easily handled by agronomists and crop physiologists, and we have established a monitoring network based on this system to bridge the knowledge gap between growth-chamber and open-field studies and, thus, to improve our ability to assess the potential impacts of climate change on rice production. In this paper, we describe the design of the monitoring system and its performance, outline the activities of the monitoring network, and present preliminary micrometeorological data from eight field sites.

2. Development of MINCER

To investigate the impacts of heat stress on rice production, we must obtain continuous measurements of the temperatures of susceptible organs, for example, that of the panicles. However, obtaining such continuous temperatures requires elaborate measurement systems and time-consuming work, making such studies prohibitively difficult for most agronomists. As a result, discussions of heat stress tend to be based on general surface weather data observed at nearby weather stations, even though those may provide only crude estimates of the temperatures to which plants are actually exposed.

As a practical compromise to the direct measurement of panicle temperature, we have focused on measuring the air temperature around the panicle; this measurement process is considerably easier and the temperatures obtained will be considerably closer to the panicle temperature than air temperatures observed at remote weather stations. Unfortunately, most commercially available meteorological instrument packages are not well designed for use within crop canopies, and their installation requires special knowledge and considerable labor (e.g., the installation of wiring between the components in muddy and flooded paddy fields).

Thus far, sensors protected by naturally ventilated radiation shields have been most often used, because they require no electricity for ventilation. However, use of such shields can lead to measurement errors because when they are heated by solar radiation in the daytime, they emit longwave radiation into the cavity where the sensors are housed, causing unpredictable increases in the temperature detected by the sensors protected by the shield. Moreover, cooling of the shields at night by outward radiation can cause unpredictable decreases in the temperature around the shield-protected sensors. The magnitude of the increase or decrease depends on environmental factors such as the intensity of radiation and wind speed, which can vary widely both temporally and spatially, making it difficult to compare results obtained on different occasions or at different sites. Although the use of force-ventilated radiation shields can mitigate this problem, they require substantial amounts of electricity to generate the ventilation, and it can be difficult to supply this electricity to paddy fields.

To overcome these difficulties, we developed MINCER (Micrometeorological Instrument for the Near-Canopy Environment of Rice), a stand-alone system with a solar-powered, force-ventilated radiation shield for accurate monitoring of air temperature (T_a) and relative humidity (RH) within a rice canopy (Fukuoka et al., 2012).

1) Design and Structure

In MINCER, we integrated all of the functions required for measurement of T_a and RH within a rice canopy into a single lightweight unit that weighs only 3.2 kg (Fig. 1). The device has a unique L-shaped flow pathway like that of the meat grinder it resembles. The intake is located at the end of the horizontal part of the L, and the outlet is at the top of its vertical part. Thus, MINCER samples air from the layer of interest, such as at the level of the panicles, and the sampled air flows out of MINCER above the canopy, thereby reducing the risk that it will affect the air in the layer of interest (Fig. 2). The device is mounted on a stable tripod (F740, Slik Corp.,

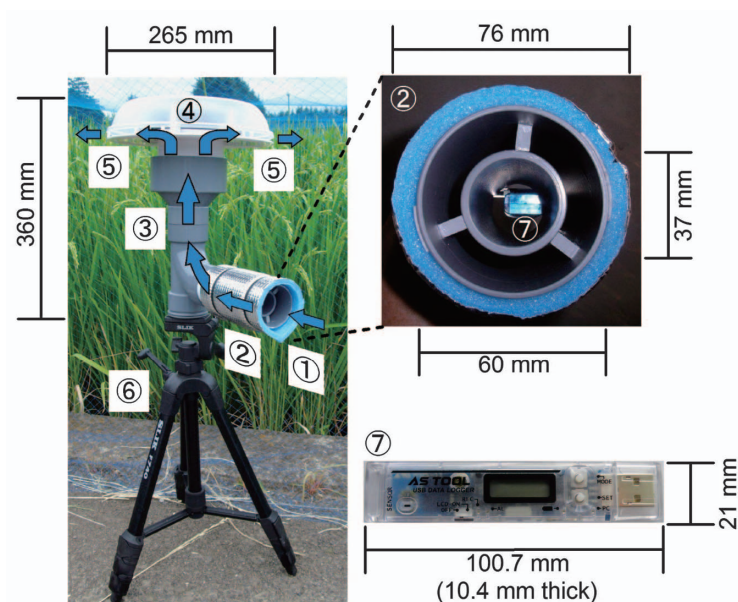


Fig. 1 A MINCER device and its components: (1) Air inlet; (2) double-hulled PVC pipe (length, 15 cm) covered with polyethylene foam insulation and clad in aluminum (also shown in cross section); (3) single-hulled PVC pipe; (4) solar-powered ventilator with rechargeable batteries; (5) air outlet; (6) tripod; and (7) datalogger (inside the horizontal double-hulled pipe), which records temperature and relative humidity. Sample air flows along the path shown by the arrows (modified from Fukuoka et al., 2012).



Fig. 2 Photograph of a MINCER device installed in a rice plant community (modified from Fukuoka et al., 2012).

Saitama, Japan), allowing it to be easily installed at the desired height.

A force-ventilated radiation shield with a double-hulled structure and a reflective surface performs better than one with a single-hulled structure (Hosono et al., 1988). MINCER's horizontal duct therefore consists of a double-hulled PVC pipe covered with polyethylene foam and clad in aluminum. This approach protects the sensors inside the device from heat. T_a and RH of the continuously sampled air are measured at user-designated time intervals as the air passes over a small temperature and humidity datalogger (RX-350TH, As One Co., Osaka, Japan, or LS350-TH, Osaka Micro Computer Inc., Osaka, Japan) located in the inner pipe. The datalogger, which resembles a USB flash drive, includes an integrated digital temperature and humidity sensor (SHT11 Version 4; SENSIRION AG, Staefa, Zurich, Switzerland), a microcomputer for logging the data, and a small lithium battery (CR1220) to permit independent operation. It can store up to 15 000 data points, which can be retrieved by a computer via a USB connection. According to the product's datasheet (SENSIRION, 2010), its accuracy is typically $\pm 0.4^\circ\text{C}$ for temperature and ± 3.0 percentage points for RH , both at 25°C . The long-term drift of the sensor is less than $0.04^\circ\text{C year}^{-1}$ for temperature and less than 0.5 pp year^{-1} for RH . Each SHT11 sensor is individually calibrated by the manufacturer in a precision humidity chamber, and the calibration coefficients that are used to internally calibrate the signals are programmed into the one-time-programmable memory on the chip.

A solar-powered ventilator attached to the top of the vertical part of the duct provides active ventilation. We used a modified version of the SolarVENT MPV #70441 ventilator (ICP Solar Technologies, Inc., Montreal, Quebec, Canada). Solar cells on top of the ventilator serve as the primary power source, which is backed up by two AA-sized rechargeable NiMH batteries connected in series. According to the manufacturer's specifications, the airflow is $34 \text{ m}^3 \text{ h}^{-1}$.

The original SolarVENT MPV #70441 ventilator always works at full speed, but the airflow required by a force-ventilated radiation shield varies depending on the heat load it receives. Because a much lower ventilation speed is generally required at night, when the heat load is less than during the day, keeping the fan operating at full speed during the night would waste energy stored in the batteries. Moreover, because the internal circuitry of the ventilator functions only to prevent overcharging, the batteries can be ruined if they become discharged completely while irradiance levels are continuously low. To solve these problems, we replaced the original circuit board with a proprietary board that we developed for MINCER that provides the following functions within the same size constraints:

- The fan motor is controlled by pulse-width modulation (PWM; 100% duty cycle in the presence of light (day), 33% duty cycle at a frequency of 15 Hz in the absence of light (night) on the board.
- Overdischarge-protection circuitry cuts the supply of electricity to the fan motor when the battery voltage reaches or falls below the lower limit of 2.1 V.
- Overcharge-protection circuitry limits the maximum charging voltage of the batteries to an upper voltage limit of 3.1 V.

To optimize the use of stored energy, we replaced the original NiMH rechargeable batteries with alternatives that have less tendency to self-discharge (Eneloop HR-3UTG, Sanyo Electric

Co. Ltd., Osaka, Japan; typical capacity, 4.8 W h).

The solar-powered ventilator of MINCER must be positioned above the canopy so that it obtains maximum power from solar radiation and to prevent the exhausted sampled air (which may have become heated while passing through the device) from disturbing micrometeorological conditions within the canopy; this is achieved by directing the exhaust away from the layer being studied. In MINCER's standard configuration, the vertical distance between the solar cells and the intake is 28 cm. Therefore, the sampling height should be no more than 28 cm below the canopy top. The sampling height above ground level can be adjusted between 57 and 154 cm by adjusting the standard F740 tripod.

These dimensional specifications have been optimized for measurement of the air surrounding rice panicles, but they can be modified as needed by using a different type of tripod or a longer vertical duct.

2) Performance

Electromechanical performance

The ventilation velocity of a MINCER device was tested under both daytime conditions and simulated nighttime conditions in a dark room. During the trial, power was supplied to the fan motor by a laboratory DC power supply (ISO-TECH IPS303DD, RS Components Ltd., Northamptonshire, UK); the voltage and current supplied were monitored by using the built-in display. While we varied the supplied voltage between 2.2 and 3.1 V, we measured the ventilation velocity with a hot-wire anemometer (V-01-AND2N, I Denshi Giken Co., Ltd., Ebina, Kanagawa, Japan). Its probe was inserted perpendicular to the direction of the airflow at a position near MINCER's temperature and humidity sensor, via a 4-mm-diameter hole that was bored through the pipe for the purpose of this test.

Figure 3 shows the relationship between the supplied voltage and the ventilation velocity around the sensor. As the voltage increased, the ventilation velocity increased, and the trends were well fitted ($R^2 \geq 0.98$) by parabolic curves under both daytime and nighttime conditions. Under the daytime conditions, the velocity ranged between 2.2 and 2.9 $\text{m}\cdot\text{s}^{-1}$. Under the simulated nighttime conditions, the pulse-width modulation chopping reduced the power consumption by 66%, thereby reducing the ventilation velocity to between 0.4 and 0.9 $\text{m}\cdot\text{s}^{-1}$, which was about 25% of the daytime velocity.

The power consumed with a 100% duty cycle was 139 mW at a typical battery voltage of 2.4 V, and that consumed with a 33% duty cycle was 46 mW. Assuming a 12-h day and a 12-h night, the total power consumption of a MINCER device during 2 days and 3 nights would be 5.0 W h. Because the MINCER batteries can typically store 4.8 W h of electricity when fully charged, most of the electricity required for 2 days and 3 nights of continuous operation can be supplied without generating solar power. This ventilation system thus eliminates the time-consuming labor that was formerly required to install electrical wiring to power a monitoring system and therefore enables anyone to start continuous measurements of air temperature and humidity within a rice canopy simply by placing a MINCER device within the canopy.

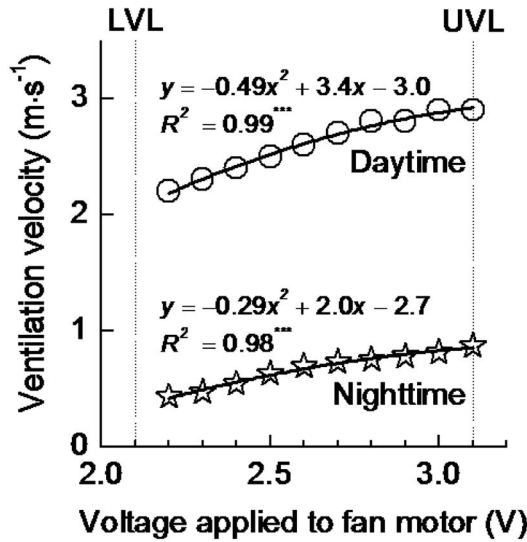


Fig. 3 Relationship between the voltage applied to the MINCER fan motor and the ventilation velocity around the temperature and humidity sensor. LVL, lower voltage limit; UVL, upper voltage limit; ***, statistically significant at $P < 0.001$ (modified from Fukuoka et al., 2012).

Performance in an open field

To test the performance of MINCER under open-field conditions, we compared T_a and RH observed with a MINCER device with values observed by a commercial system. The commercial system that we used is similar to the thermometer and hygrometer unit of the JMA-95 Automatic Weather Observing System used at meteorological observatories of the Japan Meteorological Agency. It combines a force-ventilated radiation shield (JV-250, Ogasawara Keiki Seisakusho Co., Ltd., Tokyo, Japan) with a platinum resistance thermometer (TS-801C, Ogasawara Keiki Seisakusho; Pt100 JIS Class A, with a permissible tolerance of $\pm 0.2^\circ\text{C}$ at 25°C) and a humidity and temperature transmitter (HMT333, Vaisala Oyj, Vantaa, Finland). The RH values output by the HMT333 based on its internal humidity and temperature sensors were corrected by using the T_a values observed by the TS-801C or the MINCER. The ventilation velocities around the TS-801C and HMT333 sensors were, in accordance with the manufacturer's specifications, 5 and 4 m.s⁻¹, respectively.

Downward shortwave radiation (R_{sd}) and downward longwave radiation (L_d) were measured with a pyranometer (LI-200, Li-Cor Inc., Lincoln, NE, USA) and an infrared radiometer (CG4, Kipp & Zonen B.V., Delft, the Netherlands), respectively. The R_{sd} and L_d were observed courtesy of the Weather Data Acquisition System of the National Institute for Agro-Environmental Sciences (NIAES; Tsukuba, Ibaraki, Japan). The voltage of the batteries in the MINCER was measured with a voltage datalogger (EL-USB-3, Lascar Electronics Ltd., Salisbury, Wiltshire, UK).

The trials were conducted under open-field conditions at the NIAES weather observation field

(hereafter, “OF-NIAES”) from dawn on 26 April 2011 until dusk on 1 May 2011. To investigate the effect of L_d on observed T_a during the night, the period was extended until dawn on 6 May 2011 to secure further data on the variation in L_d . The height of the air intake was set to 1.5 m above the soil surface for both instruments. The distance between the two instruments was 5.0 m.

The observed T_a values obtained with the JV-250 system and MINCER were strongly correlated ($R^2 = 0.99$, $P < 0.001$). There was a moderately strong negative correlation between the difference in the observed T_a values between the two devices ($dT_{a(M-J)} = \text{MINCER value} - \text{JV-250 value}$) and daytime R_{sd} (Fig. 4; $R^2 = 0.53$, $P < 0.001$). As R_{sd} increased, $dT_{a(M-J)}$ decreased at a rate of $-3 \times 10^{-4} \text{ } ^\circ\text{C} / (\text{W m}^{-2})$. Because T_a observed by MINCER did not show any tendency to be higher than that observed by JV-250 when R_{sd} was high, we concluded that MINCER’s performance during the day, when shelters tend to be heated by solar irradiance, was comparable to that of the JV-250.

There was a moderately strong negative correlation between $dT_{a(M-J)}$ and L_d at night (Fig. 5; $R^2 = 0.39$, $P < 0.001$), with very slight slope ($-2 \times 10^{-2} \text{ } ^\circ\text{C} / (\text{MJ m}^{-2} \text{ night}^{-1})$). Therefore, MINCER’s performance at night, when shelters tend to be cooled by radiative cooling, was also comparable to that of the JV-250, within the observed radiation levels.

Although the ventilation velocity of MINCER was lower than that of JV-250 both in the daytime and at night, the results showed that MINCER successfully eliminated the adverse effects of both high irradiance (high R_{sd}) and radiative cooling (low L_d) on T_a observations in the field.

Performance within a rice plant community

We tested MINCER’s performance within a rice plant community by comparing T_a observed by a MINCER device with that observed by a system using a conventional, naturally ventilated

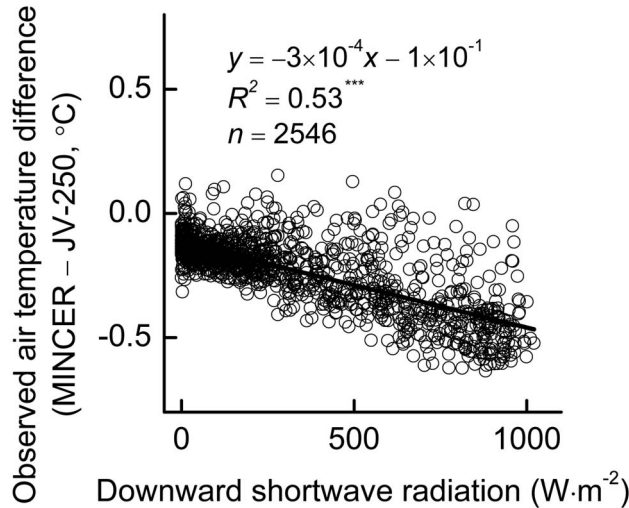


Fig. 4 The observed air temperature difference between the MINCER and JV-250 devices ($dT_{a(M-J)} = \text{MINCER value} - \text{JV-250 value}$) as a function of the intensity of the downward shortwave radiation (R_{sd}) during the day. ***, Statistically significant at $P < 0.001$ (modified from Fukuoka et al., 2012).

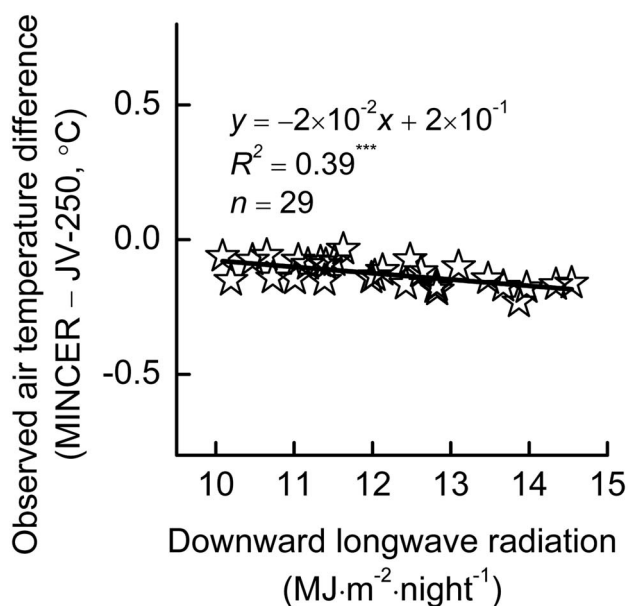


Fig. 5 The observed air temperature difference between the MINCER and JV-250 devices (dT_a (M-J) = MINCER value – JV-250 value) as a function of the intensity of the downward longwave radiation (L_d) during the night. Each data point represents the nightly average of dT_a (M-J) and the cumulative value of L_d because radiative cooling in nighttime affects the temperature change rather cumulatively than instantaneously. ***, Statistically significant at $P < 0.001$ (modified from Fukuoka et al., 2012).

radiation shield (Weather Transmitter WXT510, Vaisala Oyj). The trial was conducted in a paddy field at NIAES (hereafter, “PF-NIAES”) and at OF-NIAES from dusk on 15 September 2009 until dawn on 25 September 2009. At PF-NIAES, the MINCER and the WXT510 devices were installed in the same plant community far apart 3 rows of plant hills for avoiding interaction each other, and all observations were made at the average height of the panicles (approximately 0.8 m above the soil surface). The plant community consisted of paddy rice (‘Angelica’) grown at a planting density of 20 cm x 20 cm, and the measurements were obtained during the rice flowering stage. R_{sd} and L_d were measured with a pyranometer (MS-800; Eko Instruments Co., Ltd., Tokyo, Japan) and an infrared radiometer (PIR, Eppley Laboratory Inc., Newport, RI, USA), respectively, located at near the paddy field. Raw data were recorded at 1-min intervals by the MINCER and the WXT510 devices, and at 10-s intervals by the MS-800 and the PIR instruments. At OF-NIAES, which was located 550 m east-southeast of PF-NIAES, T_a and L_d were observed courtesy of the NIAES Weather Data Acquisition System. T_a was also measured at heights of 1.2 m above ground level with platinum resistance thermometers (OW-1-1, Ota Keiki Seisakusho Co., Ltd., Tokyo, Japan; Pt100 JIS Class A) protected by force-ventilated radiation shields (PVC-04, Prede Co., Ltd., Tokyo, Japan).

Figure 6 shows the difference between the T_a values observed by the two devices (dT_a (W-M) = WXT510 value – MINCER value) as a function of R_{sd} during the daytime period when flowering

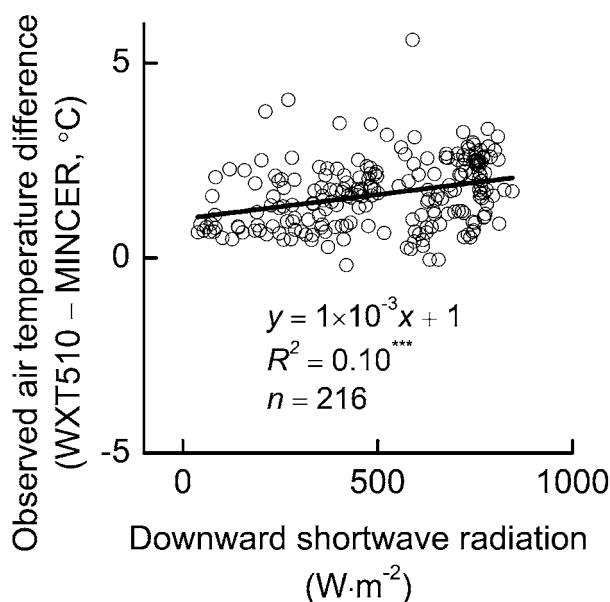


Fig. 6 The observed air temperature difference between the WXT510 and MINCER devices ($dT_{a(W-M)} = \text{WXT510 value} - \text{MINCER value}$) as a function of the intensity of the downward shortwave radiation (R_{sd}) during the typical flowering period of rice (09:00 to 13:00 LT). ***, Statistically significant at $P < 0.001$ (modified from Fukuoka et al., 2012).

typically occurs (from 09:00 to 13:00 JST). The WXT510 values became progressively higher than the MINCER values as R_{sd} increased. The magnitude of the relative rise in the WXT510 value was substantial but erratic, with the highest $dT_{a(W-M)}$ reaching 5.6°C under high irradiance ($R_{sd} = 800 \text{ W m}^{-2}$) and low wind speed (0.9 m s^{-1} at 2.5m height) condition around noon. This result can be explained as follows: In the rice canopy, where the flow of air is restricted by the plant bodies, the WXT510 shield surrounding the sensor overheated under high R_{sd} owing to insufficient natural ventilation to transfer sensible heat away from the device and into the surrounding atmosphere, leading to overheating of the sensor. Although there was a weak positive correlation between R_{sd} and $dT_{a(W-M)}$, the coefficient of determination was very low ($R^2 = 0.10$); thus, it is virtually impossible to estimate actual daytime T_a values from the WXT510 values and the $dT_{a(W-M)}$ values and the corresponding R_{sd} values.

High positive $dT_{a(W-M)}$ values were observed throughout the day on sunny days (16, 17, and 20 September 2009) (Fig. 7). Because Morita et al. (2002) reported a growth-chamber experiment in which brown rice quality was degraded by high temperatures during the day (and night), such an erratic rise in T_a during the day would make it difficult to assess the impact of heat stress on grain quality (i.e., the results might be ambiguous or even wrong). Furthermore, the time of day when flowering of rice typically occurs is slightly before (or the same as) the times when R_{sd} and $dT_{a(W-M)}$ reached their daily maximum. Because accurate observation of T_a within the canopy during flowering is especially important for studies of HISS, such a severe artifact by naturally ventilated radiation shields in measurement of T_a at flowering times is not

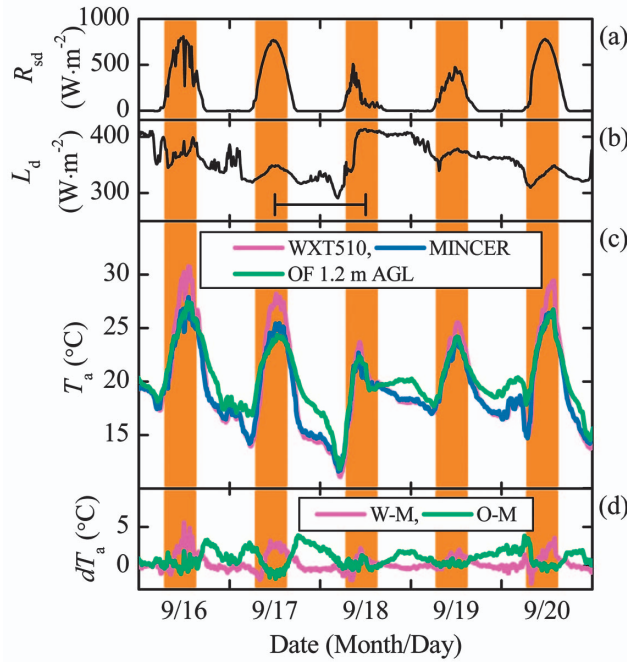


Fig. 7 Time courses of changes in (a) R_{sd} , (b) L_d , (c) T_a , and (d) dT_a (W-M) during the first 5 days of the measurement period. All data, except for the T_a data obtained in the NIAES weather observation field (OF) at 1.2 m above ground level (AGL), “OF 1.2 m AGL”, were obtained at the NIAES paddy field. R_{sd} , downward shortwave radiation; L_d , downward longwave radiation in the paddy field; T_a , observed air temperature; dT_a , difference in T_a (W-M = WXT510 value – MINCER value; O-M = “OF 1.2 m AGL” value – MINCER value). Vertical orange bars indicate the typical hours of rice flowering (09:00 to 13:00 LT) (modified from Fukuoka et al., 2012).

acceptable at all. Therefore, our results suggest that the use of naturally ventilated radiation shields during the day is not appropriate for instruments that measure T_a within the rice canopy, and this is especially true for HISS-related studies.

There was a strong and significant positive correlation between dT_a (W-M) and L_d at night ($R^2 = 0.79$, $P > 0.001$) (Fig. 8). The T_a values observed by the WXT510 became progressively lower than those observed by MINCER as L_d decreased. Therefore, the WXT510 was more prone than the MINCER to an erratic drop in T_a during the night. This result can be explained as follows: Within the rice canopy, where the wind velocity was low, the WXT510 shield surrounding the sensors was radiatively overcooled at low L_d owing to insufficient natural ventilation to transfer sensible heat from the surrounding atmosphere; as a result, the sensor was overcooled. In contrast, MINCER successfully reduced this adverse effect of low L_d through slow but steady forced ventilation (Fig. 5).

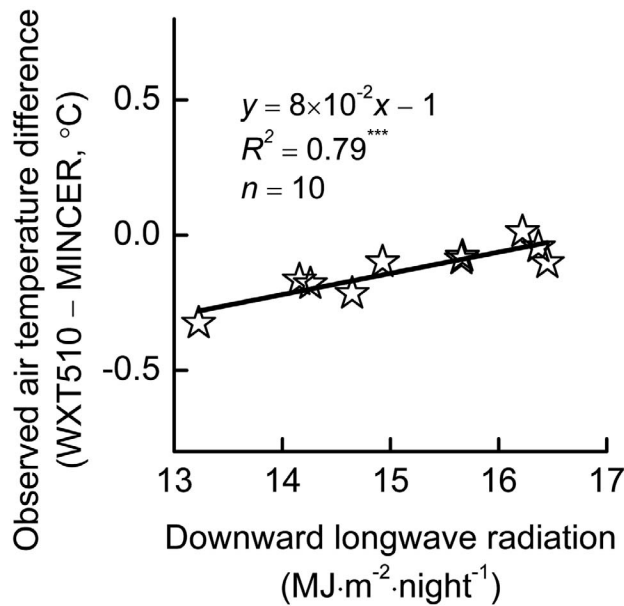


Fig. 8 Observed air temperature differences between the WXT510 and MINCER devices (dT_a (W-M) = WXT510 value – MINCER value) as a function of the intensity of the downward longwave radiation (L_d) during the night. Each data point represents the nightly average of dT_a (W-M) and the cumulative value of L_d because radiative cooling in nighttime affects the temperature change rather cumulatively than instantaneously. ***, Statistically significant at $P < 0.001$ (modified from Fukuoka et al., 2012).

Economics of MINCER

The cost of a single MINCER device, including the datalogger, is approximately ¥70 000 (about USD600) in lots of 50 units. This cost compares favorably with retail prices of approximately ¥600 000 for the JV-250 and ¥300 000 for the WXT510, both without a datalogger. Therefore, MINCER performs at least as well as these competing devices but costs considerably less.

3. Monitoring Sites and Methods

We established a monitoring network for measuring canopy thermal environments in rice paddies that we named MINCERnet, after the MINCER micrometeorological instrument (Yoshimoto et al., 2012). The initial network was deployed in eight of the world's rice-growing regions (Fig. 9).

The MINCERnet sites are experimental fields in Tamil Nadu, India (11°01'N, 76°55'E, 431 m a.s.l.); Ibbagamuwa, Sri Lanka (7°32'N, 80°27'E, 138 m a.s.l.); Mandalay, Myanmar (19°49'N, 96°16'E, 105 m a.s.l.); Los Baños, the Philippines (14°08'N, 121°16'E, 33 m a.s.l.); Hubei, China (30°20'N, 112°13'E, 36 m a.s.l.); Miaoli, Taiwan (24°29'N, 120°49'E, 105 m a.s.l.); Ibaraki, Japan (36°01'N, 140°06'E, 24 m a.s.l.); and Texas, U.S.A. (30°04'N, 94°17'W, 9 m a.s.l.).

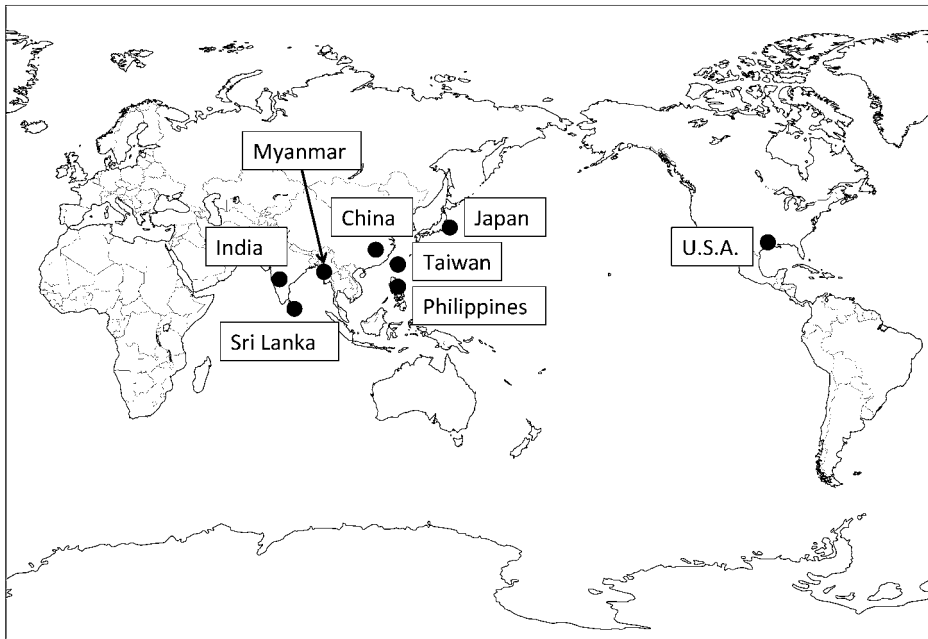


Fig. 9 Regions targeted in 2010 by the initial MINCERnet monitoring network (modified from Yoshimoto et al., 2012).

We selected these sites to cover a wide range of continental and coastal climates in low- and mid-latitude regions. Figure 10 shows the normal monthly mean air temperatures and monthly precipitation variations in the participant countries. In India, Sri Lanka, Myanmar, and the Philippines, the monthly mean air temperature is over 25°C throughout the year, and there are dry and rainy seasons, depending on the direction of the monsoon winds. In Taiwan, Hubei (China), Japan, and Texas (U.S.A.), temperatures are hotter and precipitation is higher in summer and it is colder with less precipitation in winter. The maximum monthly mean air temperature during July and August is 29°C in Taiwan, 28°C in Hubei, 25°C in Japan, and 29°C in Texas. Annual precipitation in Hubei, Japan, and Texas is generally less than in the tropical monsoon areas, but in Taiwan, it is more than 2000 mm, which is comparable to that in Sri Lanka and Myanmar. The general rice cropping calendar at each of the MINCERnet sites is shown in Fig. 11. In tropical zones such as India, Sri Lanka, and Myanmar, two or more rice crops are grown each year. In the Philippines, rice is conventionally cultivated in the dry season. In the temperate zones (Hubei, China, Japan, and Texas, U.S.A.) and in the subtropical zone (Taiwan), rice is cultivated during the summer, when temperatures and precipitation are higher.

At each site, field trials are conducted in three replicate plots with a standard cultivar. Fields are flooded and use the management practices that are conventional for each study region. Each plot is large enough to maintain a uniform microclimate within the rice canopy. One MINCER device is installed inside each plot, at least 5 m from the nearest plot edge to avoid edge effects, and it monitors air temperature, T_a , and relative humidity, RH , at panicle height for a period of

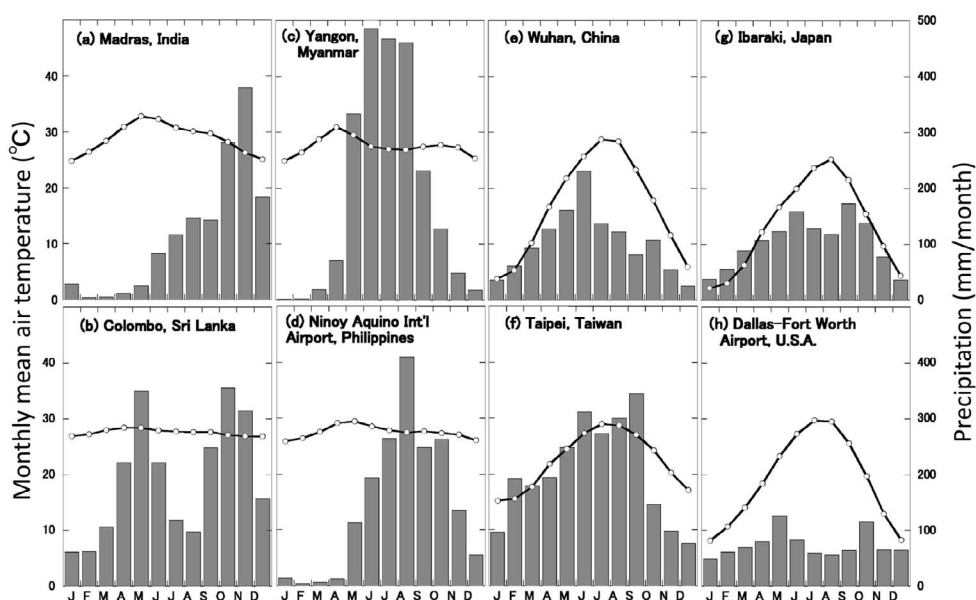


Fig. 10 Normal values of monthly mean air temperature and monthly precipitation variations in the MINCERnet participant regions/countries. All of the data are from National Astronomical Observation of Japan, 2011 (modified from Yoshimoto et al., 2012).

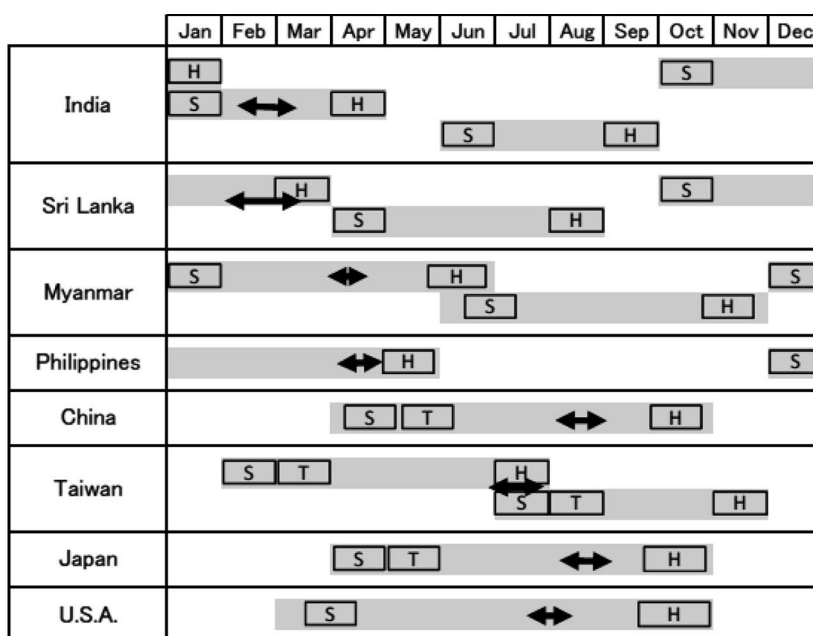


Fig. 11 General rice cropping calendars in the MINCERnet participant countries. S, sowing; T, transplanting; H harvesting. The double-headed arrows show the periods during which micrometeorological measurements were made in 2010 in the MINCERnet fields in each country/region (modified from Yoshimoto et al., 2012).

about four weeks, from rice flowering to maturity, during each cropping season. In addition, a fourth MINCER device is installed in the same field to measure T_a and RH above the rice canopy at a height set to twice the canopy height. Within and above the canopy, T_a and RH are recorded at 2-min intervals over a 24 h day.

Each replicate plot has a flowering monitoring area and a yield sampling area, in addition to the MINCER installation area. In the flowering monitoring area, temporal data on flowering (panicle emergence dates and times of flower opening) and canopy structure data (canopy height, panicle height, and the leaf area index) at the flowering stage are collected, because these parameters are closely related to the temperature difference between the panicles and the ambient air. In the yield sampling area, the sterility percentage, general yield components, and grain quality are measured at maturity.

4. Preliminary Results from MINCERnet

The purpose of MINCERnet is to fill the knowledge gap between growth-chamber and open-field experiments in studies of the impacts of climate change by measuring the thermal environment experienced directly by plants under open-field conditions. The micrometeorological data, which are obtained by using a common methodology across sites in different climate zones, together with the crop data that result from these growing conditions, will improve our quantitative understanding of the impacts of climate change on rice communities. We report here the results of preliminary analyses of micrometeorological data collected in 2010. Table 1 shows the periods when the micrometeorological data were collected by MINCERnet; these periods correspond to the flowering-to-maturity period at each site.

1) Daily Variations

Figure 12 shows typical daily changes in T_a and RH above the canopy during the flowering-to-maturity period in the MINCERnet rice paddy fields. The daily maximum T_a , which is

Table. 1 Periods of micrometeorological measurement, from rice flowering to maturity, in the MINCERnet fields (data from Yoshimoto et al., 2012).

Sites	Measurement periods
India	2010 February 13 – March 8
Sri Lanka	2010 February 3 – March 9
Myanmar	2010 March 31 – April 19
The Philippines	2010 April 2 – April 29
China	2010 August 3 – August 30
Taiwan	2010 June 30 – July 26
Japan	2010 August 7 – September 7
The U.S.A	2010 July 21 – August 9

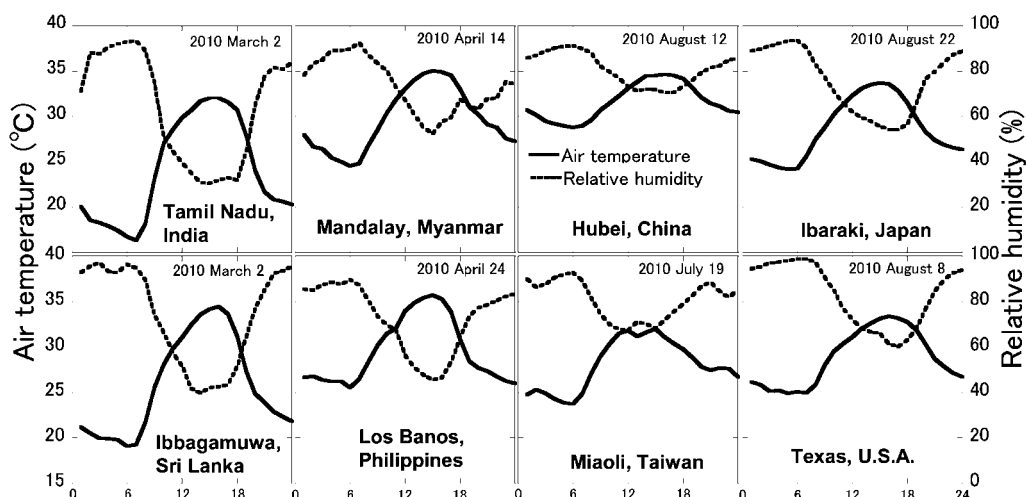


Fig. 12 Typical daily changes in air temperature (solid lines) and relative humidity (dashed lines) above the rice canopy during the period from rich flowering to maturity, assessed in each MINCERnet rice paddy (modified from Yoshimoto et al., 2012).

commonly used in analyses at growth-chamber experiments or crop models as the variable that is correlated with HISS, ranged from 32 to 36°C across all sites. Depending on the climate, however, the minimum nighttime T_a varied more widely, ranging from 17 to 28°C, and the daily amplitude of the change in T_a ranged from 6°C at the site in Hubei, China, to 15°C at the sites in India and Sri Lanka. The nighttime T_a and the daily amplitude of the T_a change are closely related not only to grain quality but also to HISS, because rice plants have a heat susceptible stage before flowering when the effects of elevated nighttime temperatures on sterility are second only to the effects of high temperature at the flowering stage (Satake and Yoshida, 1978).

Relative humidity during the daytime also differed greatly among the sites. Although the relative humidity fluctuated along with T_a in response to daily weather changes, the daily minimum RH was often 40% or less at the sites in India and Sri Lanka, whereas it was never less than 50% at those in Myanmar, Hubei, Taiwan, Texas, and Japan; it was especially high (around 70%) at the sites in Hubei and Taiwan. Because RH strongly affects the degree of evaporative cooling of the plant canopy, the canopy and panicle temperatures are likely to be lower than the T_a above the canopy at the sites in India and Sri Lanka, whereas the high humidity in Hubei and Taiwan is likely to reduce evapotranspirational cooling, resulting in increased canopy temperatures. Therefore, the daytime temperatures of the rice canopy and panicles are likely to differ greatly among sites, even when the daily maximum T_a is similar.

2) Differences of T_a and RH between Air within and above the Canopy

Figure 13 shows the T_a and RH values at the eight study sites above and within the rice canopy, averaged over the period between 10:00 and 12:00 LT each day; this period is generally considered to be the time of day that rice flowers (Kobayasi et al., 2009). The RH above the

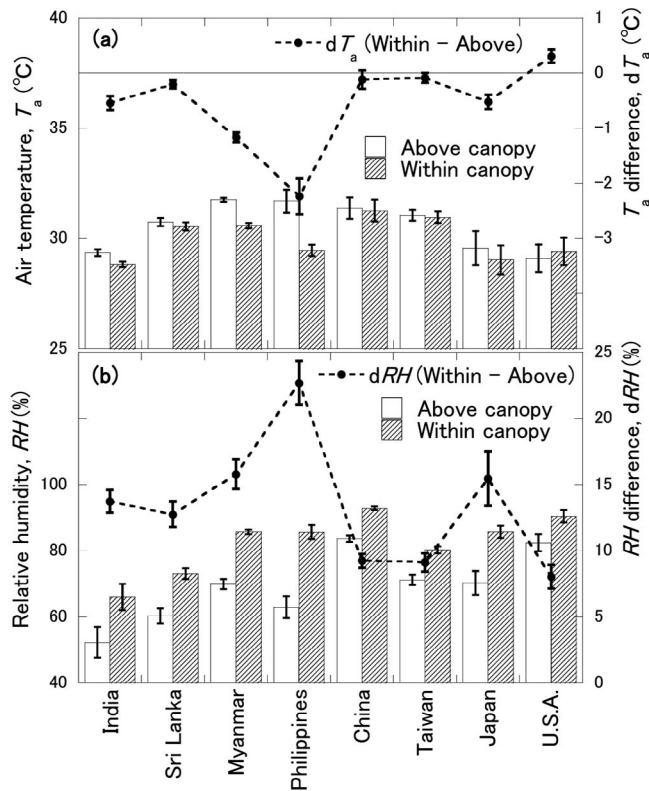


Fig. 13 (a) Air temperature (T_a) and (b) relative humidity (RH) above and within the rice canopy, and the difference in (a) T_a (dT_a) and (b) RH (dRH) between the air within and that above the canopy (dashed lines), during the general flowering time (averaged from 10:00 to 12:00 LT) (modified from Yoshimoto et al., 2012).

canopy was lowest at the site in India, followed by the sites in Sri Lanka and the Philippines. At these three sites, T_a within the canopy tended to be lower than T_a above the canopy, because dry air enhances canopy evapotranspiration, leading to greater evaporative cooling of the plant canopy and a decrease of T_a within the canopy. In contrast, where RH above the canopy was high (at the sites in Hubei and Texas), T_a within the canopy was close to (Hubei) or even higher than T_a (Texas) above the canopy.

The T_a gradient between the air within and above the canopy can be explained to some extent by the effect of RH on canopy evapotranspiration. However, the magnitude of this T_a difference did not necessarily coincide with the RH distribution among the sites. For instance, although the RH above the canopy was similar at the sites in Myanmar, Taiwan, and Japan, the T_a decrease within the canopy was large in Myanmar but very small in Taiwan. Furthermore, among the three sites with low humidity (in India, Sri Lanka, and the Philippines), the T_a decrease within the canopy was largest in the Philippines, where the RH was higher than it was in India and Sri Lanka. The explanation is that T_a within the canopy is also affected by plant traits such as physical structure, leaf area index, and canopy transpiration, as well as by RH and other

meteorological factors (e.g., solar radiation and wind speed) through their effects on the heat balance between the canopy and the air. It is noteworthy that as the RH difference between the air within and that above the canopy becomes larger, the T_a decrease within the canopy also tends to be larger (Figs. 13a and b, dashed lines). This relationship implies a “trade-off” between evapotranspiration and its cooling effect. Larger canopy evapotranspiration causes both the T_a decrease and the RH increase to be larger within the canopy. Therefore, the T_a difference between the air within and that above the canopy can be largely explained by differences in canopy evapotranspiration due to differences in plant traits such as leaf area and transpirational conductance among sites. To quantify the mechanisms that control the thermal environment within the canopy, it is thus essential to analyze these relationships by using the data collected by MINCERnet together with a heat balance model (for example, Yoshimoto et al., 2005; 2011) that accounts for the effects of these plant traits.

RH within the canopy varied over a wide range among the sites, depending on both the climate and plant canopy traits. This variation is important: RH is one of the key variables used in heat stress studies because it directly affects panicle temperatures via its effects on panicle transpiration. At the six MINCERnet sites (excluding those in India and Sri Lanka) where RH within the canopy was high, the panicle temperature is likely to be higher than T_a within the canopy when irradiance is high or wind speed is low, or when both conditions occur together.

3) Differences between Paddy Fields and Nearby Weather Stations

We compared T_a measured above and within the canopy with T_a at nearby weather stations. Figure 14 shows the differences between the daily mean T_a measured above the canopy and at a nearby weather station, as well as the temperature difference between the air above and within the canopy. These T_a differences are averaged over the measurement periods from flowering to maturity (Table 1). All of the nearby weather stations are located on the same research station campus and at the same altitude as the MINCERnet monitoring site, and none of the stations are at urbanized sites. The distance between the weather station and the MINCERnet site was around 500, 300, 600, 560, and 800 m at the sites in the Philippines, Hubei, Taiwan, Japan, and Texas, respectively. Even though the weather stations were at non-urbanized sites close to the MINCERnet monitoring sites and T_a is measured by force-ventilated radiation shield, T_a at the weather stations was typically higher than T_a above the canopy (Fig. 14, upper bars), because the stations were not in paddy fields. T_a within the canopy near the panicles was lower than T_a above the canopy (Fig. 14, lower bars) because of canopy evapotranspiration, as discussed in the previous section.

These differences suggest that if general weather station data are applied directly in heat stress studies, errors in the magnitude and variability of the results will arise owing to temperature differences between the weather stations and the field sites, thereby obscuring the differences among sites. At the site in the Philippines, for instance, the daily mean T_a above the canopy was 0.76°C lower than that at the weather station, and T_a within the canopy was 1.6°C lower than that above the canopy, resulting in a total difference of 2.4°C between the T_a directly experienced by plants within the canopy and that measured at the weather station. The magnitudes of these

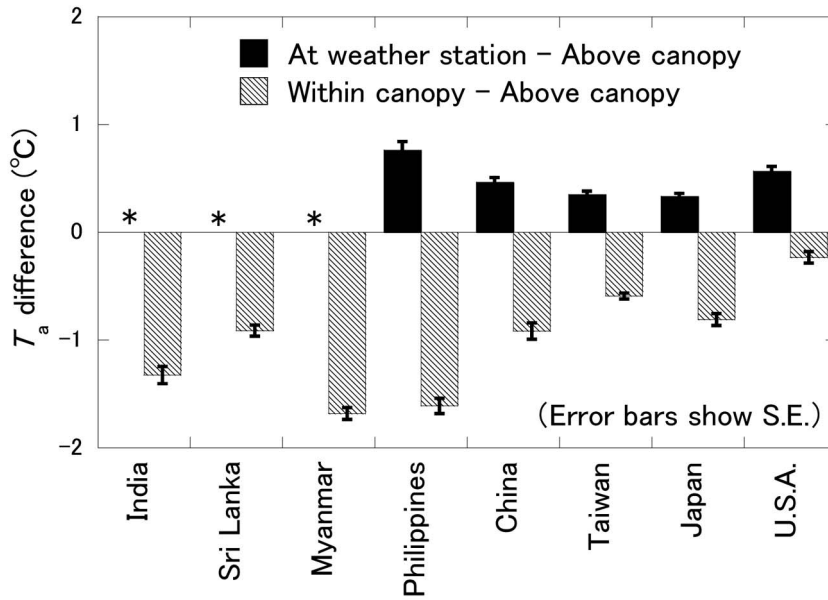


Fig. 14 Differences between the daily mean air temperature (T_a) measured above the canopy and at a nearby weather station (upper bars), and between T_a measured above and within the canopy (lower bars). *, no daily mean T_a data available at a nearby weather station. Values represent means \pm S.E. during the measurement period (see Table 1) (modified from Yoshimoto et al., 2012).

differences in daily values were large enough to greatly affect the plant response predicted by a simple crop growth model that uses cumulative temperatures, or by a rice development model such as those of Horie et al. (1995), Bouman et al. (2001), and Tao et al. (2008). These differences would similarly affect the results of heat stress analyses.

Another key problem is that the observed differences in T_a were not constant; they varied among the sites because the effect of canopy cooling by evapotranspiration differed depending on both the climate and plant canopy traits. At the site in Texas, for instance, the difference in daily mean T_a between the air above and that within the canopy was 0.23°C , which is much less than the corresponding difference at the site in the Philippines, mostly because of the wetter climate at the Texas site; these differences resulted in a net difference of 0.8°C between T_a within the canopy and that measured at the weather station, even though the T_a difference between the weather station and the air above the rice paddy was just 0.57°C .

On the basis of the preliminary findings presented here, we expect MINCERnet to contribute greatly to our quantitative understanding of the factors that affect air temperatures around rice plants. Data from this network will be useful for parameterizing climatic and environmental factors and plant canopy traits in various models, thereby reducing uncertainties in predictions of future crop production according to predicted climate change over the next century.

5. New Phase of MINCERnet

On the basis of investigations of HISS in field-grown rice, Matsui (2009) reported that HISS becomes detectable at a daily maximum T_a of around 35°C, and that T_a over 40°C can lead to substantial decreases in fertility. High nighttime temperatures, furthermore, adversely affect grain yield (Peng et al., 2004; Cheng et al., 2009), single-grain weight, and brown rice quality (Morita et al., 2002). Peng et al. (2004) reported that rice grain yield declined by 10% for each 1°C increase in the minimum growing-season temperature during the dry season, whereas the effect of the maximum temperature on crop yield was insignificant; they pointed out that a greater fundamental understanding of the effects of nighttime temperatures on the physiological processes that govern crop growth and yield is needed. Cheng et al. (2009) reported that high nighttime temperatures during the rice reproductive growth stage reduced the stimulatory effect of elevated CO₂ on brown rice yield; they pointed out that more field studies of the interactions between elevated CO₂ and nighttime temperatures performed under artificially increased nighttime temperatures to simulate future climate warming scenarios are needed to confirm their growth-chamber results. Morita et al. (2002) reported that, in a growth-chamber experiment, single-grain weight was reduced by high nighttime temperatures, whereas brown rice quality was degraded by high temperatures whether during the day or at night. These studies show that there is high demand for an instrument that can accurately observe T_a within the rice canopy at night under field conditions.

The grain-ripening period of rice after flowering is about 40 days long, so the effect of T_a on grain ripening can be cumulative. As a result, in studies of the effect of heat stress on ripening, even a very small error in observed T_a should be eliminated if possible, even though the absolute value of the erratic temperature differences during the night was generally smaller than that during the day (e.g., dT_a (W-M) in Fig. 7d). Therefore, MINCER devices have a clear advantage over systems with naturally ventilated radiation shields as an instrument for T_a observation within the rice canopy at night and also, needless to say, in the daytime.

The rice canopy micrometeorological data that we obtained by using a standardized methodology across sites in different climate zones, when combined with crop data, will improve our understanding of the impacts of future climate change on rice communities. Our preliminary micrometeorological data showed that RH , the daily amplitude of the T_a change, and nighttime T_a differed greatly among the eight sites in the network, and all of these factors strongly affect panicle temperatures and rice reproduction processes. The T_a difference between the air above and within the canopy varied widely, depending on the RH in each region; therefore, both factors are useful for characterizing the susceptibility of rice to heat. T_a at the nearby weather stations was higher than that above the rice canopy, and, because weather stations are generally not located in paddy fields, this difference must be carefully accounted for in future studies. T_a within the canopy, near the panicles, was lower than T_a above the canopy, and the magnitude of the difference varied among the regions, because the magnitude of canopy evapotranspirational cooling depends on the regional climate as well as on plant canopy traits.

Since 2014, three African sites, in Benin, Senegal, and Ghana, have been added to

MINCERnet, which now covers a wider range of climate conditions and different paddy ecosystems. In the next phase of MINCERnet research activity, we plan to conduct experiments that focus on adaptation strategies for the future, for example, by using a heat-tolerant rice variety. Heat-tolerant varieties of rice have been recently developed (e.g., Jagadish et al., 2008), but whether their introduction in a given region will be effective likely depends on the climate zone. Changes in rainfall patterns cause both heat and drought stress, but the effects of such stresses on yield and quality will differ among regions owing to differences in the micrometeorological changes caused by the rainfall changes among regions and sites. Quantification of heat stress processes, acting through canopy micrometeorology, among different climate zones and evaluation of the global distribution of crop vulnerability to heat and drought stresses are urgently needed. It is now possible to achieve both these aims, by applying our novel instrument, MINCER, and by exploiting our global research alliance, MINCERnet, which has deployed instruments in regions with widely varied climates. Thus, we are hopeful that MINCERnet will increasingly provide data that can reduce uncertainties in predictions of future crop production under climate change.

Acknowledgement

We would like to gratefully and sincerely thank all the MINCERnet participants for their enthusiastic cooperation; Dr. T. Matsui (Gifu University), Prof. XH Tian (Yangtze University, China), Prof. C. Vijayalakshmi (Tamil Nadu Agricultural University, India), Dr. T. T. Myint (Department of Agricultural Research, Myanmar), Dr. WMW Weerakoon (Field Crops Research and Development Institute, Sri Lanka), Prof. HS Lur (National Taiwan University, Taiwan), Dr. L. Tarpley (Texas AgriLife Research, USA), Dr. K. Jagadish (Kansas State University, USA) and Dr. N. L. Manigbas (Philippine Rice Research institute, Philippines). This study was supported in part by the “Multilateral Research Exchange Project for Securing Food and Agriculture” sponsored by the Agriculture, Forestry and Fisheries Research Council, Ministry of Agriculture, Forestry and Fisheries of Japan.

References

- IPCC, 2013. Working Group I. Contribution to the IPCC Fifth Assessment Report in Climate Change 2013: The Physical Science Basis, Summary for Policy Makers.
- Bouman, B.A.M., Kropff, M.J., Tuong, T.P., Wopereis, M.C.S., ten Berge, H.F.M. and van Laar, H.H., 2001. ORYZA2000: Modeling lowland Rice, International Rice Research Institute, Los Baños, the Philippines, and Wageningen University and Research Centre, Wageningen, the Netherlands, 235 pp.
- Cheng, W., Sakai, A., Yagi, K. and Hasegawa, T., 2009. Interactions of elevated [CO₂] and night temperature on rice growth and field, *Agr. Forest Meteorol.*, 149: 551–58.
- Fukuoka, M., Yoshimoto, M. and Hasegawa, T., 2012. MINCER: A novel instrument for monitoring the micrometeorology of rice canopies, *J. Agr. Meteorol.*, 68: 135–147.
- Horie, T., Nakagawa, H., Centeno, H.G.S. and Kropff, M., 1995. The rice crop simulation model SIMRIW and its testing, In: Modeling the Impact of Climate Change on Rice Production in Asia [Matthews R. B., Kropff, M. J., and Bachelet, D. (eds.)], CAB International, Oxon, UK, pp. 51–66.

- Hosono, T., Hirobe, A. and Aoki, M., 1988. Measurement errors of air temperature caused by types of shelter and rates of aspiration, *J. Agr. Meteorol.*, 44: 215–218. [In Japanese with English title]
- Jagadish, S.V.K., Craufurd, P.Q. and Wheeler, T.R., 2008. Phenotyping parents of mapping populations of rice for heat tolerance during anthesis, *Crop Sci.*, 48: 1140–1146.
- 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]
- Kobayasi, K., Masui, H., Atsuta, Y., Matsui, T., Yoshimoto, M. and Hasegawa, T., 2009. Flower opening time in rice – cultivar difference and effect of weather factors –. Proc. MARCO Symp. 2009: W2–12.
- Matsui, T., 2009. Floret sterility induced by high temperatures at the flowering stage in rice (*Oryza sativa* L.), *Jpn. J. Crop Sci.*, 78: 303–311. [in Japanese with English abstract]
- Matsui, T., Kobayasi, K., Nakagawa, H., Yoshimoto, M., Hasegawa, T., Reinke, R. and Angus, J., 2014. Lower-than-expected floret sterility of rice under extremely hot conditions in a flood-irrigated field in New South Wales, Australia, *Plant Prod. Sci.*, 17(3): 245–252.
- Morita, S., Shiratsuchi, H., Takahashi, J. and Fujita, K., 2002. Effect of high temperature on ripening in rice plants: Comparison of the effects of high night temperatures and high day temperatures, *Jpn. J. Crop Sci.*, 71: 102–109. [in Japanese with English abstract]
- National Astronomical Observatory of Japan (ed.), 2011. Rika Nenpyo (Chronological Science Tables), Maruzen, Japan, 1054 pp. [in Japanese]
- Peng, S., Huang, J., Sheehy, J.E., Laza, R.C., Visperas, R.M., Zhong, X., Centeno, G.S., Khush, G.S. and Cassman, K.G., 2004. Rice yields decline with higher night temperature from global warming. *Proc. Natl. Acad. Sci. USA*, 101: 9971–9975.
- Satake, T. and Yoshida, S., 1978. High temperature-induced sterility in indica rices at flowering, *Jpn. J. Crop Sci.*, 47: 6–17.
- Tao, F., Hayashi, Y., Zhang, Z., Sakamoto, Y. and Yokozawa, M., 2008. Global warming, rice production, and water use in China: Developing a probabilistic assessment, *Agr. Forest Meteorol.*, 148: 94–110.
- Yoshimoto, M., Fukuoka, M., Hasegawa, T., Matsui, T., Tian, X., Vijayalakshmi, C., Singh, M.P., Tin Tin Myint, Weerakoon, W.M.W., Lafarge, T., Lur, H.S. and Tarpley, L., 2012. MINCERnet: A global research alliance to support the fight against heat stress in rice, *J. Agr. Meteorol.*, 68: 149–157.
- Yoshimoto, M., Fukuoka, M., Hasegawa, T., Utsumi, M., Ishigooka, Y. and Kuwagata, T., 2011. Integrated micrometeorology model for panicle and canopy temperature (IM²PACT) for rice heat stress studies under climate change, *J. Agr. Meteorol.*, 67: 233–247.
- Yoshimoto, M., Oue, H., Takahashi, H. and Kobayashi, K., 2005. The effects of FACE (Free-Air CO₂ Enrichment) on temperatures and transpiration of rice panicles at flowering stage, *J. Agr. Meteorol.*, 60: 597–600.
- Yoshimoto, M., Yokozawa, M., Iizumi, T., Okada, M., Nishimori, M., Masaki, Y., Ishigooka, Y., Kuwagata, T., Kondo, M., Ishimaru, T., Fukuoka, M. and Hasegawa, T., 2010. Projection of effects of climate change on rice yield and keys to reduce its uncertainties, *Crop Environ. Bioinformatics*, 7(4): 260–268.