Punched-top chamber for moderately raising air temperature during the ripening period in rice

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ABSTRACT
Rice growth at an elevated air temperature \( T_{\text{air}} \) during the ripening period is often evaluated using a semi-closed chamber (SCC). However, the water vapor pressure deficit (VPD) and CO\(_2\) concentration inside SCCs get lower than at ambient air plot, and these changes affect panicle temperature and photosynthesis. We developed a punched-top chamber (PTC), that is, an SCC with numerous pores on the top, and compared meteorological environments inside the two chambers and of ambient air plot. When solar radiation was >200 W m\(^{-2}\), \( \Delta T_{\text{air}} \) (SCC – Ambient) was 3.1°C–5.3°C, and \( \Delta T_{\text{air}} \) (PTC – Ambient) was 2.2°C–3.7°C. Excessively high \( T_{\text{air}} > 38°C \) were more frequent inside the SCC than the PTC. The changes in VPD and CO\(_2\) concentration inside the PTC were less pronounced compared with those of the SCC, and thus PTC can be a better treatment for safely assessing the direct effect of elevated \( T_{\text{air}} \).

Introduction
The increase in air temperature \( T_{\text{air}} \) due to the global climate change has various effects on crop production. The most commonly used method for raising \( T_{\text{air}} \) during the ripening period in rice is a semi-closed chamber (SCC), which is a closed-top and open-sided plastic greenhouse. The SCC raises the daily maximum \( T_{\text{air}} \) by 5.3°C–5.9°C and the daily mean \( T_{\text{air}} \) by 2.5°C–3.0°C without a thermal source for 30 days after heading (Komaki et al., 2002); moreover, SCCs can be easily constructed at low cost (Chiba & Terao, 2014). However, SCCs excessively raise \( T_{\text{air}} \) during the evaluation of the effects of high \( T_{\text{air}} \) on grain filling and appearance quality. Komaki et al. (2002) reported that a 20–30 cm open-sided SCC raised the \( T_{\text{air}} \) up to 40°C, which led to a significant increase in infertile
grains as well as unmatured and dead grains. In this condition, an effect of the interaction between genotypes and $T_{\text{air}}$ on the percentage of undamaged grains was not observed, although this interaction is important for the selection of genotypes with heat tolerance. Ishizuki et al. (2013) developed an SCC with a length of the open side that was automatically controlled. This can avoid excessive heat stress on rice plants; however, the installation of the automatic control system requires more effort and is more costly than the simple SCC.

An open-top chamber (OTC), which was originally developed to evaluate the effect of high CO$_2$ and air pollution, also raises $T_{\text{air}}$ inside the chamber (Heagle et al., 1979). For grassland, the increases in $T_{\text{air}}$ observed inside OTCs differed according to plant species, chamber design, and environment (Leadley & Drake, 1993). The $T_{\text{air}}$ increase was proportional to the solar radiation (Whitehead et al., 1995), and the daytime increase ranged from 0°C to 4.3°C (Heagle et al., 1979; Messerli et al., 2015; Moya et al., 1997; Olszyk et al., 1980; Weinstock et al., 1982; Whitehead et al., 1995). In a flooded paddy field, Chiba and Matsumura (2006) reported that an OTC increased the daytime $T_{\text{air}}$ by as little as 0.5°C, which is lower than that detected for grassland. Thus, those authors developed new OTCs fitted with solar heated tunnels in subsequent studies (Chiba & Terao, 2014; Terao & Chiba, 2016); the new chambers increased the midday $T_{\text{air}}$ by about 1°C. However, the $T_{\text{air}}$ increase afforded by the OTC is smaller than that afforded by the SCC, and a simpler design would be preferable for the establishment of multiple chambers and for the evaluation of large amounts of plants, because the construction of heating tunnels also requires effort and additive materials.

The increases in $T_{\text{air}}$ inside both the SCC and the OTC are related to the fact that the cover of the chamber prevents gas exchanges between inside and outside the chamber. Therefore, the water vapor pressure deficit (VPD) and CO$_2$ concentration, in addition to $T_{\text{air}}$, are different between inside and outside the chambers (Norby et al., 1997; Weinstock et al., 1982; Whitehead et al., 1995). To date, the manners in which VPD and CO$_2$ concentration inside the chambers are affected by the SCC design have been ignored during the evaluation of rice growth. In the other warming chamber, temperature gradient chamber, CO$_2$ concentration and VPD can be adjusted to match the outside environments by controlling the rates of air ventilation and CO$_2$ injection (Horie et al. 1995), but SCCs in a normal design have no adjustment function.

We developed a new chamber for raising $T_{\text{air}}$ during the ripening period of rice, namely the punched-top chamber (PTC). The PTC is an SCC with numerous pores on the top. The PTC with a design that is intermediate between the SCC and the OTC may afford an average $T_{\text{air}}$, VPD, and CO$_2$ concentration. The objective of our study was to clarify the differences in VPD and CO$_2$ concentration as well as $T_{\text{air}}$ between the SCC, PTC and ambient air, to prove that the PTC is a useful alternative to the SCC for the evaluation of plant performance at high $T_{\text{air}}$. As a guideline for the PTC to be an alternative, we aimed at least 2°C increase during midday inside PTCs compared with ambient air, a decreased frequency of excessive high $T_{\text{air}}$ (>38°C), and smaller changes in VPD and CO$_2$ concentration than inside SCCs. We also used the micrometeorology model, IM$^2$PACT (Yoshimoto et al., 2011) to estimate effects of the micromclimates inside the chambers on panicle temperatures ($T_{\text{pan}}$).

**Materials and Methods**

**Plant cultivation**

The experiments were conducted at the paddy field of the Central Region Agricultural Research Center, NARO, in Joetsu, Niigata, Japan (37°9’N, 138°16’E) in 2017 and 2018. We transplanted medium-sized seedlings of the Dontoki cultivar to a paddy field on 16 May 2017 and 11 May 2018. The plant density was 22.2 plants m$^{-2}$ (30 × 15 cm) at the rate of two plants per hill. All chemical fertilizers were applied as basal and were composed of 7 g N m$^{-2}$ coated urea (LP100 that releases 80% of the nitrogen at a uniform rate until 100 days after application), 4 g m$^{-2}$ P$_2$O$_5$, and 4 g m$^{-2}$ K$_2$O. Plants were grown under flooded conditions with 2-week mid-drainage from 30 days after transplanting, and were protected from diseases and insects using chemicals. The heading dates were August 4 and August 2, and plant maturity was achieved on September 18 in 2017 and September 15 in 2018, respectively.

**Warming treatments**

In a field, three treatment plots consisting of ambient air plot, SCC plot, and PTC plot were set with two replicates in 2017 and three replicates in 2018. Each plot of 1.8 m × 1.8 m was assigned in a completely randomized design in a field (>206 m$^{-2}$) in two years. The distance between the plots was longer than 2.4 m. The SCC and PTC were installed from one week after heading dates to plant maturity. The SCC and PTC were developed by covering a rectangular
metal frame with two transparent plastic films of the ceiling and side (0.1 mm thickness; Daich Vinyl, Fukui, Japan), with the frame being based on the design described by Chiba and Terao (2014). When it rained, the films of ceiling and side were separated under the weight of the accumulated water on top of the SCCs unlike PTCs, and the recorded data during these periods were excluded from the analysis. The sizes of the frames were a 1.8 × 1.8 m horizontal square with a height of 1.5 m for the SCC, and a 1.8 × 1.8 m square with a height of 1.3 m for the PTC (Figure 1). The 0.2 m lower height of the PTC was aimed at shortening the time of gas exchange between the inside and the outside of the chamber by decreasing the volume covered with the plastic films. The top of the PTC had approximately 162 pores (9 × 18) with a diameter of 3 cm and a spacing of 20 × 10 cm cut using a compass fitted with a razor. Preliminary tests suggested that (1) \( T_{air} \) did not change when area-percentage of hole/top was the same even though the hole spacing and diameter were different (PTC-A vs. PTC-B, Table S1), (2) the halved area of the holes did not improve the increase in \( T_{air} \) (PTC-A vs. PTC-C), and (3) a doubled area of the holes or increased open length of the side decreased the \( T_{air} \) increase (PTC-A vs. PTC-D, PTC-E). In the present study, the open length of the side was set at 0.35 m for both PTCs and SCCs (Figure 1) to enhance \( T_{air} \) increase during the daytime, rather than the preliminary test side open length of 0.5 m (PTC-A). Light transmittance of the top film of SCCs measured by a light analyzer (LA-105; NK System, Osaka, Japan) was 94%, and the hole area of the top of the PTC was 3.5%. Thus, the holes of the PTC only increased light transmittance by 0.2% compared to SCC.

### Collection of meteorological data

\( T_{air} \) and relative humidity were measured at a central location of each ambient air plot, SCC plot, and PTC plot at a height of 1.0–1.1 m above the ground surface, which is the height of the panicles and flag leaves at heading. These measurements were done in two plots for each treatment in 2017 and 2018, although there was no replicate for ambient air plot in 2018, for the period from August 16 to September 14 in 2017 and from August 11 to September 13 in 2018.

\( T_{air} \) and relative humidity were recorded by a sensor with logging function (Hygrochron; KN Laboratories, Inc., Osaka, Japan) in 2017, and by a sensor (HMP50 or HMP60; VAISALA, Helsinki, Finland) attached to a data logger (CR-10X; Campbell Scientific Inc., Utah, USA) in 2018. These sensors were set inside an aspirated radiation shield that moved air at 20 m³ h⁻¹ (Fan Aspirated Solar Radiation Shield 380–283; Novalynx Corp, California, USA) in the two years. Exceptionally, one logger of two replicates for ambient air plot in 2017 was set inside another type of aspirated radiation shield, NIAES-09 (Fukuo et al., 2011). \( T_{air} \) and relative humidity were measured at 30 min intervals in 2017 and at 10 min intervals in 2018. VPD (hPa) and relative humidity were calculated by \( T_{air} \) (°C) and relative humidity (RH, %) using the following equation (Murray, 1967).

\[
VPD = 6.1078 \times 10^{7.5 \text{Tair}/(\text{Tair}+237.3)} \times (1 - \text{RH}/100)
\]

Solar radiation and wind speed at a height of 6 m were measured at 1 min intervals at a meteorological station located 300 m distant in a same experimental field. The wind speed measured at the meteorological station was significantly correlated with the wind speed measured at a height of 3 m in the tested paddy field (\( r = 0.649, P < 0.001 \)), with the latter being 0.462-fold the former, on average (Figure S1). The mean daily \( T_{air} \) and mean daily solar radiation from heading to plant maturity were 24.6°C and 14.7 MJ m⁻² d⁻¹ in 2017, and 25.4°C and 14.2 MJ m⁻² d⁻¹ in 2018, respectively.

### Calculation of panicle temperature

In order to estimate the effect of microclimate changes inside the plant canopy caused by the chamber application on \( T_{pan} \), the micrometeorological model, IM²PACT (Yoshimoto et al., 2011) was applied to the measured data at ambient air, PTC and SCC plots. IM²PACT is a physical model that solves for the heat balance inside the canopy obtaining the \( T_{pan} \) as the solution, and the main input variables are \( T_{air} \), RH, solar radiation, and wind speed. The measured values of \( T_{air} \) and RH inside the canopy of each treatment were directly given as input values. For solar radiation, the value of the meteorological station was given for the ambient air plot, and the values of 94.2% and 94% of it were given for the PTC and SCC plots, respectively, according to the light transmission characteristics of the chamber film. The input value of wind speed above the canopy for ambient air plot was given by the value at 6 m height of the meteorological
station multiplied by the above ratio of 0.462. The wind speeds for PTC and SCC plots were set assuming that the chamber application would reduce the wind level to 1/10 of the level in the ambient air plot. Since there is no actual measurement of wind speed in the chamber, the reduction to 1/10 was set as a reference, but the actual wind speed may be lower than that because there is almost no wind in the chamber. For the panicle transpiration conductance and the bulk canopy transpiration conductance, the values of Akitakomachi cultivar (Yoshimoto et al., 2011) were applied as typical values for Japanese cultivars because of no actual measurements.

**Measurements of CO$_2$ concentration inside the chambers**

The CO$_2$ concentrations near panicles and flag leaves were measured in the center of the ambient air plot, SCC plot, and PTC plot using three replicates in 2018. The measurements were made in the daytime from August 24 to 30 in 2018, and the clock time during the measurement was different by day in order to vary solar radiation and wind speed. The air was aspirated at a height of 1.1 m by a flow control pump (minipump MP-Σ300, SIBATA scientific technology LTD, Tokyo, Japan) at the rate of 1.0 L min$^{-1}$ through a nylon tube, and the air for each plot was manually switched using a three-way valve. Next to the pump, the air was introduced into a 200 mL Erlenmeyer flask, to lessen the fluctuation of CO$_2$ concentration by stirring the air, and passed through a 1-μm air filter (Merk Millipore, Mass., USA) and a membrane gas dryer (SWC-M04-70/IP; AGC Engineering CO. LTD., Chiba, Japan). The CO$_2$ concentration was measured by an infrared gas analyzer (LI-820; LI-COR, USA) at 5 s intervals, and the concentration at each plot at a given time was determined as a mean for three consecutive recorded values at a stable state. Because the volumes of the SCC and PTC covered with plastic film were larger than 3078 L, the effect of gas absorption at the rate of 1.0 L min$^{-1}$ on the measured values of CO$_2$ concentration was negligible.

**Statistical analysis**

Analysis of variance (ANOVA) and Tukey’s post hoc (Tukey-HSD) tests for multiple comparisons among the treatments were performed on the values for $T_{air}$, VPD, $T_{pan}$, and CO$_2$ concentration. ANOVAs were performed using a mixed model, with treatment and year as dependent variables, and measurement time as a random effect for $T_{air}$, VPD and $T_{pan}$. For CO$_2$ concentration, the model had treatment as a dependent variable and measurement time as the random effect. Statistical analyses were carried out using JMP 14.3.0 (SAS Institute Inc., Cary, NC, USA) statistical software.

**Results**

In 2017, the solar radiation during the warming treatments from August 10 to September 16 was comparative to the mean for the 10 years from 2007 to 2016, while in 2018, solar radiation was below the mean till noon (Figure 2). The solar radiation greater than 200 W m$^{-2}$ is expected from 8:00 to 16:00 in the 10 years, and from 10:00 to 14:00 for the 25th percentile. When solar radiation was larger than 200 W m$^{-2}$, there was a significant difference in $T_{air}$ (p < 0.05), with SCC, PTC, and ambient air plot being higher in that order (Table 1). The $\Delta T_{air}$ (SCC – Ambient) and $\Delta T_{air}$ (PTC – Ambient) were enhanced under a greater solar radiation and smaller wind speed. When solar radiation was 0 W m$^{-2}$ at nighttime, the $T_{air}$ inside the two chambers was 0.6°C–1.4°C lower than that detected in the ambient air plot. Similarly to $T_{air}$, the calculated $T_{pan}$ values inside the SCC and PTC were significantly higher than the ambient air plot when solar radiation >0 W m$^{-2}$ (p < 0.05, Table 2). The $\Delta T_{pan}$ (SCC – Ambient) and $\Delta T_{pan}$ (PTC – Ambient) were 2.5°C–3.6°C greater than the respective $\Delta T_{air}$ values when solar radiation >200 W m$^{-2}$.

Figure 3 shows the frequency distribution of $T_{air}$ inside the SCC and PTC when $T_{air}$ in ambient air plot was higher than 30°C and solar radiation ≥200 W m$^{-2}$. Frequency of high $T_{air}$ was higher in the SCC than the PTC; frequencies of >38°C were 33.3% in 2017 and 7.8% in 2018 in the SCC, and those of PTC were 3.9% and 1.0%, 

![Figure 2](image-url) **Figure 2.** Diurnal course of solar radiation averaged from August 10 to September 16 in 2017 and 2018 at the experimental site. The solid line represents the yearly mean of solar radiation for the same period from 2007 to 2016, and the dashed lines represent the 75th and 25th percentiles.
Table 1. Air temperature near panicles in the ambient air plot (Ambient) and inside the warming chambers at different solar radiations (S, W m⁻²) and wind speeds in 2017 and 2018.

| Wind speed | Main effect | S ≥ 200 | 200 > S > 0 | S = 0 (night) |
|------------|-------------|---------|-------------|--------------|
| < 2 m s⁻¹ | Ambient | 26.2 | c | 23.9 | c | 23.1 | a |
|            | SCC | 31.5 | a (5.3) | 24.8 | a (0.9) | 22.5 | b (–0.6) |
|            | PTC | 30.0 | b (3.7) | 24.6 | b (0.7) | 22.5 | b (–0.6) |
| 2017       | 28.7 | b | 23.4 | b | 22.6 | b |
| 2018       | 29.8 | a | 25.4 | a | 22.8 | a |
| ≥ 2 m s⁻¹  | Ambient | 28.0 | c | 24.4 | b | 23.9 | a |
|            | SCC | 31.1 | a (3.1) | 24.7 | a (0.3) | 22.7 | b (–1.2) |
|            | PTC | 30.2 | b (2.2) | 24.2 | c (0.2) | 22.5 | c (–1.4) |
| 2017       | 28.1 | b | 23.1 | b | 22.4 | b |
| 2018       | 31.4 | a | 25.8 | a | 23.7 | a |

P value
< 2 m s⁻¹ treatment < 0.01 < 0.01 < 0.001
< 2 m s⁻¹ year < 0.01 < 0.01 < 0.001
≥ 2 m s⁻¹ treatment < 0.01 < 0.01 < 0.001
≥ 2 m s⁻¹ year < 0.01 < 0.01 < 0.001

Air temperature (°C) was recorded at 30 min intervals from August 16 to September 14 in 2017, and at 10 min intervals from August 10 to September 10 in 2018. SCC, semi-closed chamber; PTC, punched-top chamber. The same letters following the values indicate non-significant differences among treatments within each solar radiation and wind speed condition, according to Tukey’s test (P < 0.05). Values within parentheses represent the difference from Ambient.

respectively. The daily mean $T_{air}$ on fine days with a daily solar radiation >20 MJ m⁻² d⁻¹ was 1.8°C higher in the SCC and 1.0°C higher in the PTC compared with the ambient air plot (Table 3). An increase in daily mean $T_{air}$ was not observed on days with a daily solar radiation <15 MJ m⁻² d⁻¹.

The changes in VPD inside the SCC and PTC varied with environmental conditions (Table 4). The VPDs inside the SCC were significantly higher than the ambient air plot at wind speed <2 m s⁻¹ and solar radiation >200 W m⁻² (p < 0.05). In the other conditions, the VPDs inside the SCC were significantly lower than those of the ambient air plot (p < 0.05). In both situations, the PTC exhibited a similar or smaller difference in VPD vs. ambient air plot, compared with the SCC. The difference in $T_{air}$ and VPD between the two replicates of measurement tended to get larger when solar radiation >0 W m⁻² compared to solar radiation = 0 W m⁻² (Table S2).

The CO₂ concentration inside the warming chambers was significantly lower than that detected in the ambient air plot (p < 0.05, Table 5). The decreases in CO₂ concentration inside the warming chambers were greater at wind speed <2 m s⁻¹. At this condition, CO₂ concentration inside the SCC was significantly lower than that inside the PTC, and the CO₂ concentrations were higher in the ambient air plot.

Table 2. Estimated panicle temperature in the ambient air plot (Ambient) and inside the warming chambers at different solar radiations (S, W m⁻²) and wind speeds in 2017 and 2018.

| Wind speed | Main effect | S ≥ 200 | 200 > S > 0 | S = 0 (night) |
|------------|-------------|---------|-------------|--------------|
| < 2 m s⁻¹ | Ambient | 27.1 | c | 23.4 | c | 20.8 | a |
|            | SCC | 35.4 | a (8.4) | 25.3 | a (1.9) | 19.8 | b (–1.0) |
|            | PTC | 34.5 | b (7.4) | 25.1 | b (1.7) | 19.8 | b (–1.0) |
| 2017       | 31.8 | b | 25.5 | b | 18.5 | b |
| 2018       | 32.8 | a | 25.7 | a | 21.7 | a |
| ≥ 2 m s⁻¹  | Ambient | 27.7 | c | 23.6 | c | 21.8 | a |
|            | SCC | 33.3 | a (5.6) | 24.4 | a (0.8) | 20.4 | b (–1.4) |
|            | PTC | 32.3 | b (4.7) | 23.9 | b (0.3) | 20.2 | c (–1.6) |
| 2017       | 29.9 | b | 22.9 | b | 19.4 | b |
| 2018       | 32.3 | a | 25.0 | a | 22.3 | a |

P value
< 2 m s⁻¹ treatment < 0.01 < 0.01 < 0.001
< 2 m s⁻¹ year < 0.01 < 0.01 < 0.001
≥ 2 m s⁻¹ treatment < 0.01 < 0.01 < 0.001
≥ 2 m s⁻¹ year < 0.01 < 0.01 < 0.001

Panicle temperatures were calculated using IM2PACT (Yoshimoto et al., 2011) based on the measured values of air temperature and relative humidity. SCC, semi-closed chamber; PTC, punched-top chamber. The same letters following the values indicate non-significant differences among treatments within each solar radiation and wind speed condition, according to Tukey’s test (P < 0.05). Values within parentheses represent the difference from Ambient.
inside the SCC and the PTC were 86 μmol mol⁻¹ (21%) and 46 μmol mol⁻¹ (11%) lower than that in ambient air plot, respectively (p < 0.05).

**Discussion**

The SCC exhibited not only increases in $T_{\text{air}}$ (Table 1) but also changes in VPD (Table 4) and decreases in CO₂ concentration (Table 5), which indicates that the environmental factors including VPD and CO₂ concentration other than $T_{\text{air}}$ may affect grain filling of the plants inside the SCC. A decrease in CO₂ concentration around the plant canopy decreases the photosynthesis rate (Farquhar & Sharkey, 1982), and a reduction in the carbon assimilate supply during grain filling increases the percentage of chalky grains (Tsukaguchi & Iida, 2008). The dewdrops present at the top when VPD is small and ventilation is low reduces light transmittance (Harazono et al., 1997), and dewdrops were often observed on the cover of an SCC (data not shown).

The microclimate inside the PTC was intermediate between those of the SCC and ambient air plot; the reduction in CO₂ concentration inside the PTC was almost half of that in the SCC at low wind speed <2 m s⁻¹ (Table 5), and the changes in VPD inside the PTC were similar to or smaller than those of the SCC (Table 4). Unlike SCCs, almost no dewdrops were observed at the top of PTCs, probably due to ventilation through pores. The $\Delta T_{\text{air}}$ (PTC – Ambient) was 2.2°C–3.7°C when the solar radiation was > 200 W m⁻² (Table 1), which was larger than 1.0°C, reported for the improved OTC fitted with solar heated tunnels (Chiba & Terao, 2014; Terao & Chiba, 2016). There was less opportunity for $T_{\text{air}}$ inside the PTC to reach excessively high values >38°C (1.0–3.9%) than in the SCC (7.8–33.3%), when the outside $T_{\text{air}}$ was >30°C (Figure 3). The excessively high $T_{\text{air}}$ of >38°C around flowering time increases the percentage of infertile grains (Matsui, 2009), which complicates the evaluation of grain filling and apparent quality (Komaki et al., 2002). In addition to the decreased frequency of high $T_{\text{air}}$, the PTC achieved the target values of $T_{\text{air}}$ and had less changes in VPD and CO₂ concentration (Tables 4 and 5), and thus the PTC was determined to be a better method than the SCC for safely assessing the direct effect of high $T_{\text{air}}$.

**Table 3.** Daily mean air temperature of the ambient air plot (Ambient) and inside the semi-closed chamber (SCC) and punched-top chamber (PTC).

| Daily solar radiation | Year | Date   | Ambient | SCC  | PTC     | Remarks |
|-----------------------|------|--------|---------|------|---------|---------|
| <15 MJ m⁻² d⁻¹        | 2017 | Aug 16 | 26.0    | 25.7 | 25.6    | Typhoon |
|                       |      | Aug 31 | 21.8    | 23.3 | 22.6    |         |
|                       |      | Sep 11 | 25.0    | 25.7 | 25.3    |         |
|                       | 2018 | Aug 24 | 29.9    | 28.5 | 27.9    | Typhoon |
|                       |      | Sep 7  | 23.9    | 24.0 | 23.8    |         |
|                       |      | Sep 12 | 21.6    | 21.7 | 21.5    |         |
| mean                  |      |        | 23.7    | 24.1 | 23.7    | (0.4)   | (0.0)   |
| >20 MJ m⁻² d⁻¹        | 2017 | Aug 21 | 27.5    | 29.6 | 28.8    |         |
|                       |      | Aug 27 | 24.4    | 27.1 | 25.6    |         |
|                       |      | Sep 1   | 22.3    | 24.7 | 23.5    |         |
|                       |      | Sep 2   | 22.2    | 24.0 | 23.1    |         |
|                       |      | Sep 9   | 23.0    | 25.3 | 24.1    |         |
|                       |      | Sep 10  | 23.4    | 25.2 | 24.3    |         |
| 2018                  | Aug 12 | 26.1 | 27.6    | 27.3 | 27.3    | Foehn   |
|                       | Aug 14 | 28.9 | 29.6    | 29.2 | 29.2    | Foehn   |
|                       | Aug 22 | 30.4  | 30.0    | 29.5 | 29.5    |         |
|                       | Aug 23 | 30.1  | 29.2    | 28.7 | 28.7    | Foehn   |
|                       | Sep 1  | 22.0  | 22.7    | 22.8 | 22.8    |         |
| mean                  |      | 24.4  | 26.2    | 25.4 | 25.4    | (1.8)   | (1.0)   |

The rain fall in the listed days was < 5 mm. The daily temperature of the days with Foehn and Typhoon winds was excluded from the calculation of average temperature. Here, Foehn wind is defined as a 10 min average wind stronger than 3 m s⁻¹ for at least 2 h. The temperatures of fine days from 17 to 21 August 2018 had failed to be record. Values within the parenthesis represent the difference from Ambient.

Plant body temperature, such as $T_{\text{pant}}$, is greatly affected by environmental factors other than $T_{\text{air}}$, especially by humidity and wind speed through the effect of evaporative cooling of the plant body (Yoshimoto et al., 2011). For both SCC and PTC, the chamber application
blocks the diffusion of water vapor from plant transpiration and water surface evaporation to the air above the chamber, so the absolute humidity inside the chambers always increased compared to ambient air plot at all solar radiation and wind speed conditions (data not shown). At solar radiation ≥200 W m⁻² and wind speed <2 m s⁻¹, the increase in T_air inside both the SCC and PTC relative to ambient air plot was large (especially inside the SCC, with an extreme increase of 5.3°C; Table 1), where VPD apparently increased slightly (Table 4) due to the increase in saturated water vapor pressure. However, at other solar radiation and wind speed conditions, VPD decreased (Table 4). The applying of these T_air and humidity changes inside the SCC and PTC to IM²PACT with the assumption of the wind speed to be reduced to 1/10 of that of ambient air plot showed that the increase in T_pan by the chamber application was greater than that of T_air for both the SCC and PTC in terms of heat balance (Table 2). This suggests that the chamber application increases T_pan, more than the increase in T_air, which is applicable for investigating physiological responses to T_air increase in the ripening stage of rice canopy. We note, however, that the wind speed in both SCC and PTC was set to be 1/10 of the ambient air plot in this simulation, so the increase in T_pan was calculated to be similar between SCC and PTC (Table 2), but the actual wind speed could be lower, especially in SCC since there was almost no wind, and the increase in T_pan could be even greater in SCC than this simulation.

In our study, while the T_air inside both the SCC and PTC was higher than that in the ambient air plot when the solar radiation was >0 W m⁻² in the daytime, the T_air was lower inside the chambers when solar radiation was 0 W m⁻² in the nighttime (Table 1); similar differences were observed for T_pan (Table 2). T_air changes in a day occur near the water surface and plants first, and then the T_air change is transmitted to the above air (Geiger & Stewart, 1950). When the chambers are applied into the plant canopy, the heat balance in nighttime is such that the covers of the chamber themselves, in addition to the plant canopy, act as a cold source against the warmer above air. The observed T_air difference at night, where the temperature inside the chambers was lower than that in the ambient air plot, is because the SCC and PTC plots are surrounded by more cold sources (the cooled cover of the chambers as well as the plant canopy) than the ambient air plot. The phenomenon of lower T_air than the outside at night in greenhouse or chamber without heating system has been reported in the previous studies (Chiba & Terao, 2015; Harazono et al., 1997; Terao & Chiba, 2016). These results indicate that the SCC and PTC in this study are not suitable for experiments focusing on high night temperatures. Although ΔT_air (SCC – Ambient) and ΔT_air (PTC – Ambient) were proportional to solar radiation in

Table 4. Water vapor pressure deficit near panicles for the ambient air plot (Ambient) and inside the warming chambers at different solar radiations (S, W m⁻²) and wind speeds in 2017 and 2018.

| Wind speed | Main effect | S ≥ 200 | 200 > S > 0 | S = 0 (night) |
|------------|-------------|---------|-------------|---------------|
| < 2 m s⁻¹  | Ambient     | 8.2 b   | 3.9 a       | 2.8 a         |
|            | SCC         | 8.8 a   | 2.3 c (-1.6)| 1.2 b (-1.6) |
|            | PTC         | 8.3 b   | 2.5 b (-1.4)| 1.2 b (-1.6) |
|            | 2017        | 7.7 b   | 2.5 b       | 2.4 a         |
|            | 2018        | 9.2 a   | 3.3 a       | 1.1 b         |
| ≥ 2 m s⁻¹  | Ambient     | 12.7 a  | 6.5 a       | 7.0 a         |
|            | SCC         | 10.6 c (-2.1)| 3.6 c (-2.9)| 3.2 b (-3.7) |
|            | PTC         | 12.0 b (-0.8)| 4.1 b (-2.4)| 3.3 b (-3.6) |
|            | 2017        | 7.4 b   | 2.7 b       | 4.9 a         |
|            | 2018        | 16.1 a  | 6.8 a       | 4.1 b         |

P value:
| Wind speed | treatment | < 2 m s⁻¹ | < 2 m s⁻¹ | < 2 m s⁻¹ |
|------------|-----------|-----------|-----------|-----------|
| < 2 m s⁻¹  | treatment | < 0.01    | < 0.01    | < 0.01    |
|            | year      | < 0.01    | < 0.01    | < 0.01    |
| ≥ 2 m s⁻¹  | treatment | < 0.01    | < 0.01    | < 0.01    |
|            | year      | < 0.01    | < 0.01    | < 0.01    |

Water vapor pressure deficit was recorded at 30 min intervals from August 16 to September 14 in 2017, and at 10 min intervals from August 10 to September 13 in 2018. SCC, semi-closed chamber; PTC, punched-top chamber. The same letters following the values indicate non-significant differences among treatments within each solar radiation and wind speed condition, according to Tukey’s test (P < 0.05). Value within parentheses represent the difference from Ambient.

Table 5. CO₂ concentration around rice panicles at the ambient air plot (Ambient) and inside the semi-closed chamber (SCC) and punched-top chamber (PTC) at different wind speeds (W, m s⁻¹).

| Treatment | CO₂ concentration (μmol mol⁻¹) |
|-----------|--------------------------------|
| W ≥ 2     | W < 2                          |
| Ambient   | 403 ± 3 a                      | 402 ± 6 a                        |
| SCC       | 383 ± 19 b (-20)               | 316 ± 10 c (-10)                 |
| PTC       | 383 ± 10 b (-20)               | 356 ± 3 b (-20)                  |
| P value   | < 0.01                         | < 0.01                           |

Value represents average ± standard deviation among three replicates. Measurements were carried out from 24 to 30 August 2018. Values within parentheses represent the difference from Ambient.
daytime, the negative $\Delta T_{air}$ (warming chambers – Ambient) was observed when wind speed $>4$ m s$^{-1}$ in 2018 (Figure S2), which would have been due to the prevention of warm foehn wind induction to the chambers. Thus, the effects of warming chambers on daily mean $T_{air}$ can vary depending on the characteristics of regional climate.

The $T_{air}$ decrease in the night had a negative effect on the daily $T_{air}$ rise, but in total, daily $T_{air}$ inside the PTCs was 1.0°C higher than that in ambient air plots when daily solar radiation $>20$ MJ m$^{-2}$ d$^{-1}$ (Table 3). When daily solar radiation $<15$ MJ m$^{-2}$ d$^{-1}$, no significant increase in daily $T_{air}$ was observed. These results can be attributed to the $T_{air}$ increase during the daytime being proportional to the solar radiation inside PTCs as well as SCCs (Figure S2), as previously reported (Terao & Chiba, 2016; Whitehead et al., 1995). Thus, the PTC and SCC are effective in increasing the $T_{air}$ in regions with a strong solar radiation. The frequency of days with fine weather varies according to regions; fine weather with daily solar radiation $>20$ MJ m$^{-2}$ d$^{-1}$ is expected for an average of 46% days in August in Japan, that is, the frequency of fine days $>20$ MJ m$^{-2}$ d$^{-1}$ in August for the 10 years (from 2007 to 2016) was 45% for the experimental site, Joetsu (37°6’N), 41% for the Northern site, Daisen, Akita prefecture (39°5’N), and 55% for the southern site, Fukuyama, Hiroshima prefecture (34°5’N). The frequency of daily solar radiation $<15$ MJ m$^{-2}$ d$^{-1}$ for the same period was 25%–38% for the three sites.

We demonstrated that the PTC, which had numerous pores on the top of the SCC, exhibited at least 2°C increase in $T_{air}$ when solar radiation was greater than 200 W m$^{-2}$, with lesser frequency of excessive high $T_{air}$, and less pronounced changes in VPD and CO$_2$ concentration compared with the SCC. The changes in microclimates inside the PTC are affected by the air flow through the lower open spaces at the side, as well as from pores on the top, as seen from the fact that relationship between $T_{air}$ inside SCC and solar radiation is affected by wind speed (Figure S2). Thus, it is important to note that when installing PTCs, the targeted increase in $T_{air}$ should be adjusted by controlling the lower open spaces and height and volume of the PTC according to the regional climate and structure of the plant canopy.

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Disclosure statement

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References

Chiba, M., & Matsumura, O. (2006). High temperature treatment for rice in paddy field by breaking wind. in Japanese. Japanese Journal of Crop Science, 74, 228–229. http://dx.doi.org/10.14829/jcsproc.221.0.228.0

Chiba, M., & Terao, T. (2014). Open-top chambers with solar-heated air introduction tunnels for the high-temperature treatment of paddy fields. Plant Production Science, 17(2), 152–165. http://dx.doi.org/10.1626/pps.17.152

Chiba, M., & Terao, T. (2015). Improvement of high-temperature treatment method using solar radiation under unstable wind conditions. Plant Production Science, 18(3), 414–420. http://dx.doi.org/10.1626/pps.18.414

Farquhar, G. D., & Sharkey, T. D. (1982). Stomatal conductance and photosynthesis. Annual Review of Plant Physiology, 33(1), 317–345. http://dx.doi.org/10.1146/annurev.pp.33.060182.001533

Fukuoka, M., Kuwagawa, T., Yoshimoto, M., & Yamada, Y. (2011). A guide for building your own “NIAES-09” – A low-cost force-ventilated radiation shield utilizing construction materials. Climate in Biosphere, 11 (in Japanese), A10–A16.

Geiger, R., & Stewart, M. N. (1950). The climate near the ground. Harvard University Press.

Harazono, Y., Chen, Q., & Yoshimoto, M. (1997). Effects of dewdrop on plastic films on light transmittance, temperature and humidity in greenhouses. Journal of Agricultural Meteorology, 53(3), 175–183. http://dx.doi.org/10.2480/agrmet.53.175

Heagle, A. S., Philbeck, R. B., Rogers, H. H., & Letchworth, M. B. (1979). Dispensing and monitoring ozone in open-top field chambers for plant-effects studies. Phytopathology, 69(1), 15–20. http://dx.doi.org/10.1094/Phyto-69-15

Horie, T., Nakagawa, H., Nakano, K., Hamotani, K., & Kim, H.Y. (1995). Temperature gradient chambers for research on global environment change. III. A system designed for rice in Kyoto, Japan. Plant, Cell and Environment, 18(9), 1064–1069. https://doi.org/10.1111/j.1365-3040.1995.tb00618.x

Ishizuki, H., Kikukawa, H., & Saitoh, K. (2013). Effect of shading and high-temperature treatments on thickness and appearance quality of brown rice and palatability of cooked rice. Japanese Journal of Crop Science, 82(3), 242–251. http://dx.doi.org/10.1626/jcs.82.242

Terao, Ikuo, Takeshi, T., Chen, M., & Terao, M. (2016). High temperature treatment for rice in paddy field by breaking wind. in Japanese. Journal of Crop Science, 74, 228–229. http://dx.doi.org/10.14829/jcsproc.221.0.228.0

Terao, Ikuo, Takeshi, T., Chen, M., & Terao, M. (2016). High temperature treatment for rice in paddy field by breaking wind. in Japanese. Journal of Crop Science, 74, 228–229. http://dx.doi.org/10.14829/jcsproc.221.0.228.0
Komaki, Y., Sasahara, H., & Uehara, Y. (2002). Varietal differences of ripening ability among early-maturing rice varieties under high temperature in a vinyl house. Hokuriku Crop Science, 37 (in Japanese), 12–16. https://doi.org/10.19016/hokurikucs.37.0_12

Leadley, P. W., & Drake, B. G. (1993). Open top chambers for exposing plant canopies to elevated CO2 concentration and for measuring net gas exchange. Vegetatio, 104–105(1), 3–15. http://dx.doi.org/10.1007/BF00048141

Matsui, T. (2009). Floret sterility induced by high temperatures at the flowering stage in rice (Oryza sativa L.). Japanese Journal of Crop Science, 78(3), 303–311. http://dx.doi.org/10.1626/jcs.78.303 in Japanese with English abstract

Messerli, J., Bertrand, A., Bourassa, J., Bélanger, G., Castonguay, Y., Tremblay, G. F., Baron, V., & Séguin, P. (2015). Performance of low-cost open-top chambers to study long-term effects of carbon dioxide and climate under field conditions. Agronomy Journal, 107(3), 916–920. http://dx.doi.org/10.2134/agronj14.0571

Moya, N., Ziska, L. H., Weldon, C., Quilang, J. E. P., & Jones, P. (1997). Microclimate in open-top chambers: Implications for predicting climate change effects on rice production. Transactions of the American Society of Agricultural Engineers, 40(3), 739–747. https://doi.org/10.13031/2013.21304

Murray, F. W. (1967). On the computation of saturation vapor pressure. Journal of Applied Meteorology, 6(1), 203–204. https://dx.doi.org/10.1175/1520-0450(1967)006<0203:OTCSVP>2.0.CO;2

Norby, R., Edwards, N., Riggs, R., Abner, C., Wulischleger, S., & Gunderson, C. (1997). Temperature-controlled open-top chambers for global change research. Global Change Biology, 3(3), 259–267. https://doi.org/10.1046/j.1365-2486.1997.00072.x

Olszyk, D. M., Tibbits, T. W., & Hertzberg, W. M. (1980). Environment in open-top field chambers utilized for air pollution studies. Journal of Environmental Quality, 9(4), 610–615. http://dx.doi.org/10.2134/jeq1980.00472425000900040015x

Terao, T., & Chiba, M. (2016). An improved open-top chamber with solar-heated double funnels that can adapt to all wind directions for simulating future global warming conditions in rice paddy fields. Agricultural Sciences, 7(10), 716–731. http://dx.doi.org/10.4236/as.2016.710067

Tsukaguchi, T., & Iida, Y. (2008). Effects of assimilate supply and high temperature during grain-filling period on the occurrence of various types of chalky kernels in rice plants (Oryza sativa L.). Plant Production Science, 11(2), 203–210. https://doi.org/10.1626/pps.11.203

Weinstock, L., Kender, W. J., & Musselman, R. C. (1982). Microclimate within open-top air pollution chambers and its relation to grapevine physiology. Journal of the American Horticultural Society, 107(5), 923–929.

Whitehead, D., Hogan, K. P., Rogers, G. N. D., Byers, J. N., Hunt, J. E., McSeveny, T. M., Hollinger, D. Y., Dungan, R. J., Earl, W. B., & Bourke, M. P. (1995). Performance of large open-top chambers for long-term field investigations of tree response to elevated carbon dioxide concentration. Journal of Biogeography, 22(2/3), 307–313. https://doi.org/10.2307/2845925

Yoshimoto, M., Fukuoka, M., Hasegawa, T., Utsumi, M., Ishigooka, Y., & Kuwagata, T. (2011). Integrated micrometeorology model for panicle and canopy temperature (IM^3PACT) for rice heat stress studies under climate change. Journal of Agricultural Meteorology, 67(4), 233–247. https://doi.org/10.2480/agrmet.67.4.8