Development of an Air-Curtain Roof Chamber to Assess Climate Change Effects on Crop Plants: A Study with Rice

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To elucidate effects of climate change on growth and yield of crop plants, we developed a new growth chamber with an air-curtain shed roof. The chamber space was divided into two: one side followed outdoor temperature and the other side was several degrees higher than the outdoor temperature. Furthermore, we tried to assess the real temperature effect by achieving the same vapor pressure deficit (VPD) in two divided spaces and grew rice plants from seedling to maturity stages as an experimental material. For the high temperature (HT) plot, we adopted +4°C of the outdoor-temperature-following (control; CONT) plot because, in a preliminary experiment, +5°C of CONT induced sterility in most grains. The HT conditions advanced the day to flowering of rice, but its grain yield was lower than those obtained under CONT conditions. Trial of the same VPD under HT and CONT conditions suggested that the effect of VPD on rice growth and yield was not large during the June-October growth season.

Keywords : climate change, dry-matter production, environmental control, heat stress, Oryza sativa, yield reduction

INTRODUCTION

Recent years have brought unsettled, especially hot weather. These bouts of heat are apparently one result of global warming, induced to a considerable degree by human activities such as gigantic-scale fossil-fuel combustion and deforestation (Rosenzweig and Hillel, 1998; Brönnimann, 2015). Projected temperature rises are 2.6–4.8°C (higher scenario) to 0.5–1.7°C (lower scenario) for 2081–2100 relative to 1986–2005. The observed increase in global carbon emissions over the past 15–20 years has been consistent with the higher scenario (Hayhoe et al., 2017). Higher temperatures than those of normal seasons affect crop growth and yields depending on their intensity level and duration. Observed typical effects are hastening of leaf appearance, flowering, and maturity, increased sterility, and decreased grain weight and quality (Stone, 2001; Menzel and Sparks, 2006). Unless these human-triggered changes terminate, adaptation to them will be necessary by the breeding of tolerant crop species and varieties against these changes, or shifting of the season and location in crop cultivation (Rosenzweig and Hillel, 1998; Lafarge et al., 2011; Redden et al., 2014).

In Japan, the planting time of rice crop has advanced to a considerable degree, concurrent with the dissemination of early season culture. Therefore, grain filling often occurs during high temperatures of summertime, which degrades grain weight and quality (e.g. imperfect rice kernels including chalky grain; Nagato et al., 1960; Nagato and Ebata, 1965; Tashiro and Wardlaw, 1991). High-temperature-induced deterioration of rice production is occurring worldwide concomitantly with recent global warming (Jagadish et al., 2007; Oh-e et al., 2007; Kobata et al., 2011). As a countermeasure to this, the breeding of new rice cultivars tolerant to high temperatures which includes metabolic changes, is progressing but it is not satisfactory at present (Ishimaru et al., 2016; Morita et al., 2016; Tayade et al., 2018; Fahad et al., 2019).

To forecast crop behavior in response to global environmental changes, a series of experiments corresponding to such changes using environmental control facilities is expected to be beneficial. At present, facilities of various types such as the greenhouses and phytotrons (Went, 1957; Downs, 1980), temperature gradient chamber (TGC; Mihara, 1971; Oh-e et al., 2007), open-top chamber (OTC; Heagle et al., 1973; Drake et al., 1989), and free-air carbon dioxide enrichment (FACE; Allen et al., 1992; McLeod and Long, 1999) with natural or artificial light sources are adopted in response to experimental needs from basic to applied situations of crop performance under environmental changes (Hashimoto, 1987). In addition to these facilities, we have developed a new growth chamber, the “air-curtain roof chamber (ACRC),” with appearance that does not differ largely from that of OTC. A great difference from existing OTC is use of the ‘air-curtain’ shed roof, which functions as the ceiling without intercepting sunlight or rain. Air from the curtain source circulates...
within the chamber and protects the internal temperature and humidity from external disturbances. Furthermore, the chamber space is divisible into two: one side for outdoor conditions and the other side for different conditions from those prevailing outdoors. Therefore, this ACRC presents the respective advantages of ordinary growth chambers and OTCs simultaneously. Consequently, after the establishment of our new chamber, we examined its capability by growing rice crops under different temperatures (normal vs. high). Furthermore, we tried to elucidate the "real temperature effect" on rice plants with equivalent vapor pressure deficit (VPD) under high and normal temperatures because differences in VPD affected leaf photosynthesis and plant growth considerably (Woledge and Parsons, 1986; Imai and Kanda, 1995; Day, 2000; Lu et al., 2015).

MATERIALS AND METHODS

Chamber structure and environmental control

As presented in Figs. 1 and 2, this ACRC (W 1.9 m, D 2.4 m, H 2.3 m external size; W 1.8 m, D 1.8 m, H 1.5 m effective size) has an aluminum single-flow-roof frame (SAD-1 half type, Alumini Neo, Daisen Co., Ltd., Toyohashi, Japan) installed on the spiral pile base with 80 μm-thick ETFE film (F-CLEAN® Natural Light; AGC Green-tech Co., Ltd., Tokyo, Japan) as wall material which transmits short-to-long wave solar radiation. This ACRC is lightweight. Therefore, it is mobile, facilitating changes in the setup location. To separate the chamber space into two, a screen with ETFE film can be inserted at the central part of the chamber (north to south). The visibly open ceiling is shuttered by circulating air with two air-curtain facilities (W 0.9 m; GK-2509S, Mitsubishi Electric Corp., Tokyo, Japan) set at the south side of girders. The temperature and humidity regulations are performed with two lines of air conditioners, with four waterproof fans (φ = 0.3 m), hot-water heat exchanger, cool-water heat exchanger, dehumidifier, humidifier, air-heat-source heat pump (MDI, 2.5 kW, AC100 V, 460 W), and two cool-to-hot water heat-storage tanks (0.6 m³ with 50 mm heat-shut urethane foam). Using these, the outside-temperature-following regulation with temperature deflection and the outside-humidity-following regulation with humidity deflection are possible. Furthermore, the insertion of ETFE film at the central portion of the chamber space enables maintenance of two temperature or humidity conditions simultaneously. For the current experiment, we set one side as the outdoor-temperature-following (CONT; control) mode and another as the high temperature (HT) mode. For example, actual temperature differences of the outdoor

"Fig. 1 Schematic portrayal of the air-curtain roof chamber: AC1, 2 - air curtain; F1, 2 - fan; HC1, 2 - heating coil; CC1, 2 - cooling coil; DH - dehumidifier; WS - water spray; SH - steam humidifier; CWT - chilled water tank; HWT - hot water tank; CU - chiller unit; HP - heat pump unit; THP1, 2, 3 - temperature and humidity probe; THC1, 2, 3 - temperature and humidity converter; DL - data logger; TC1, 2 - temperature controller; HC1, 2 - humidity controller; SC - signal converter; ΔT - temperature difference setter; DB1, 2, 3 - dry bulb temperature; RH1, 2, 3 - relative humidity."
and CONT were within 0.13–1.15°C during June–August 2016. A data logger (GL-220; Graphtec Corp., Yokohama) was set to record the short-term and long-term histories of temperature and humidity during the experiment. For air-moisture control in 2015, we used a relative humidity (RH) control in which RH of HT followed that of CONT. In 2016, however, we adopted the VPD control, which targeted the same VPD (zero AVPD) between HT and CONT.

Meteorological data collection

On-site measurements of temperature and RH were conducted by setting a TR-72wF sensor with a data logger (T & D, Tokyo, Japan) at the appropriate position of measurements near rice plants in both CONT and HT plots. These sensors were intolerant to vapor-saturated air. Therefore, we removed them on rainy days. Data of RH were converted to VPDs using the saturation vapor pressure at the measured temperature.

Rice cultivation

1. Cultivation under temperature and RH control: On 8 June 2015, four germinated seeds of rice (Oryza sativa L. cv. Aichinokaori, a late cultivar) were planted in 1/5000 a Wagner pot packed with 3 kg commercial soil for rice (N: P2O5: K2O = 4: 16: 7, %). On 21 June, when the fourth leaf of the main stem had fully expanded, plants were thinned to two per pot and were waterlogged to 3-cm depth. On 11 July, plants were thinned to one per pot. On 31 August, chemical fertilizer (5 g/pot, N: P2O5: K2O = 8: 8: 8, %) was supplemented. Temperature treatments (CONT vs. HT [4°C higher than CONT]) were performed during 21 June and 14 October (harvest time) by dividing the chamber space into two parts (north to south) with a FTTH-film wall. When we performed a preliminary experiment in 2014, we adopted +5°C of CONT as HT. However, the temperature difference was so large that HT plants set small numbers of grains in most panicles (Fig. 3). Therefore, we adopt +4°C of CONT as HT, thereafter.

Twelve pots were used for each treatment. In this trial, RH was controlled to accord in both HT and CONT plots. Because our temperature and humidity sensors were intolerant to vapor-saturated air, we removed them on rainy days from the on-site. Therefore, data were sometimes lacking. Nevertheless, overall, control of the temperature difference in the ACRC seemed sufficient. Average differences of vapor pressure deficit (VPD) between HT and CONT in 2015 and 2016 were, respectively, 3.83 hPa (HT; 29.49°C, CONT; 25.66°C) and 3.90 hPa (HT; 24.78°C). Because our temperature and humidity sensors were intolerant to vapor-saturated air, we removed them on rainy days from the on-site. Therefore, data were sometimes lacking. Nevertheless, overall, control of the temperature difference in the ACRC seemed sufficient. Average differences of vapor pressure deficit (AVPD) between HT and CONT in 2015 and 2016 were, respectively, 7.48 hPa (HT; 19.13 hPa, CONT; 11.65 hPa) and 7.38 hPa (HT; 11.35 hPa, CONT; 7.57 hPa). As described in MATERIAL AND METHODS, the trial in 2015 was obtained by RH control (targeted to the same RH between HT and CONT) and that in 2016 was obtained by VPD control (targeted to the same VPD between HT and CONT).

2. Cultivation under temperature and VPD control: On 10 June 2016, rice plants (cv. Aichinokaori) were subjected to cultivation under the same fertilizer and differential temperature conditions as in 2015. In this trial, VPD was controlled as possible as the same value in both temperature treatments. Therefore, “real temperature effects” were expected. On 15 August, chemical fertilizer (5 g/pot) was supplemented. Temperature and VPD treatments were performed during 11 June through 20 October (harvest time). Sampling procedures and characterization of harvested plants were the same as those undertaken in 2015.

Data analysis

Rice plant data were compared using Tukey’s Honestly Significant Difference test after completion of one-way ANOVA using software (BellCurve for Excel 3.20; Social Survey Research Information Co., Ltd., Tokyo).

RESULTS

Temperature and humidity control

Figure 4 presents trends of the temperature and humidity controls in ACRC during rice cultivation in the 2015 and 2016 seasons. Both high temperature (HT; +4°C of the control) and control (CONT; outside-temperature-following) plots in two years showed a seasonal change with the maximum in early August. Average differences of temperature (ΔT) between HT and CONT (initial target was 4.0°C) in 2015 and 2016 were, respectively, 3.83°C (HT; 29.49°C, CONT; 25.66°C) and 3.90°C (HT; 24.78°C). Because our temperature and humidity sensors were intolerant to vapor-saturated air, we removed them on rainy days from the on-site. Therefore, data were sometimes lacking. Nevertheless, overall, control of the temperature difference in the ACRC seemed sufficient. Average differences of vapor pressure deficit (AVPD) between HT and CONT in 2015 and 2016 were, respectively, 7.48 hPa (HT; 19.13 hPa, CONT; 11.65 hPa) and 7.38 hPa (HT; 11.35 hPa, CONT; 7.57 hPa). As described in MATERIAL AND METHODS, the trial in 2015 was obtained by RH control (targeted to the same RH between HT and CONT) and that in 2016 was obtained by VPD control (targeted to the same VPD between HT and CONT).

High temperature effects on rice growth and yield

The heading time (corresponding to mid-flowering) expressed as days after sowing and the growth parameters of rice plants at harvest are presented in Table 1. In 2015, the heading time was advanced significantly (5.5 days) in HT plants compared to that in CONT plants. However, the effects of HT on other parameters were not significantly
different: leaf area (−7%), leaf numbers on main culm (+2%), plant length (+1%), culm length (+1%), and tiller numbers (+3%). In 2016, the heading time advanced (2.9 days), and plant length (−4%) and culm length (−5%) decreased, significantly by HT. However, the leaf area (−15%), leaf numbers on main culm (−1%), and tiller numbers (−7%) were not affected significantly by HT.

Table 2 presents the dry-matter production and the harvest index of rice plants at harvest. In 2015, HT plants decreased the dry weights of the panicle (−11%), leaf blade (−5%), leaf sheath + culm (−17%), root (−30%), and whole plant (−11%) significantly compared to those of CONT plants. On the other hand, under HT, the dead leaf dry weight increased (+23%) significantly and the harvest index (the ratio of panicle dry weight to whole plant dry weight) did not change. In 2016, the tendency of HT responses of dry-matter production resembled that of 2015: panicle (−35%), root (−18%), and whole plant (−16%) decreased significantly, but leaf blade (−5%), leaf sheath + culm (−5%), dead leaf (+5%), and harvest index (−8%) did not.

Yield components of rice plant at harvest are presented in Table 3. In 2015, only the grain numbers per panicle (−8%) decreased significantly by HT. Other components did not change significantly: panicle number (+2%), panicle length (0%), 1000-grain weight (−2%), or % maturity (+2%). In 2016, only the panicle numbers (−17%) decreased significantly by HT. Other components did not change significantly by HT: panicle length (+4%), grain numbers per panicle (−7%), 1000-grain weight...
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Table 3  Effects of high temperature on yield components of rice without (2015) and with (2016) controlling VPD

| Year | Plot          | Panicle number | Panicle length (cm) | Grain number per panicle | 1000-grain weight (g)* | % maturity |
|------|---------------|----------------|---------------------|--------------------------|------------------------|------------|
| 2015 | Control **    | 33.0           | 21.1                | 102.6                    | 21.97                   | 87.6       |
|      | High temperature ° | 33.6           | 21.1                | 94.6*                    | 21.62                   | 89.2       |
| 2016 | Control **    | 32.4           | 21.9                | 93.1                     | 20.99                   | 86.4       |
|      | High temperature ° | 26.9**         | 22.7                | 87.0                     | 20.37                   | 87.8       |

* Brown rice  
° Outside-temperature-following  
† +4°C of the control  
** **: Significantly different, respectively, at the 1% and 5% levels against each of the control plot, by Tukey’s Honestly Significant Difference test.

DISCUSSION

Environmental control

Figure 4 shows that results of the temperature-difference control (targeted AT = 4°C) between HT and CONT were almost satisfactory (AT = 3.83–3.90°C). However, temperature and air humidity might affect plant growth and development. For that reason, humidity effects should be eliminated if one intends to investigate “real temperature effects” from this complexity. In an experiment conducted in 2016, we tried to get the same VPD in HT and CONT (targeted ΔVPD = 0 hPa between HT and CONT). However, the trial was not necessarily perfect (ΔVPD = 3.78 hPa), although it was far better than the result obtained for 2015 (ΔVPD = 7.48 hPa), where the same RH was targeted between HT and CONT. It is noteworthy that the capacity of the humidifier used for this experiment was too low to adjust inconstant solar-energy input. Therefore, doubling the humidifier capacity is expected to alleviate this difficulty. Erickson and Markhart (2001) conducted a growth chamber trial that combined temperature and VPD (25°C/11 hPa, 33°C/11 hPa, and 33°C/21 hPa). They found that VPD (11 vs. 21 hPa) at high temperature (33°C) did not affect the flower number or fruit set of bell pepper. Lewin et al. (2017) reported that the potential for negative impacts of an elevated VPD on stomatal conductance and photosynthesis is minimal if the value is less than 5 hPa. In a paper reviewing the literature available for greenhouse tomato, Shamsiri et al. (2018) introduced optimal VPDs for growth and development of 2–12 hPa. Consequently for greenhouse tomatoes in winter, Lu et al. (2015) lowered VPD from 14 to 8 hPa by fogging and succeeded in increasing growth and productivity concomitantly with promotion of the net photosynthetic rate. According to our results of ΔVPD (7.48 hPa in 2015 and 3.78 hPa in 2016), ΔVPD apparently did not greatly affect rice plant performance. However, when conducting studies of global warming, high-temperature effects can complicate the interpretation of results because low VPD adversely affects some physiological processes, such as pollination in rice (Matsui et al., 1997). In further studies of crop plants, it is often necessary to ascertain whether effect(s) are derived from temperature or humidity or both.

Growth and yield of rice plants

With elevation of temperature (+4°C; HT) during the growth season of rice plants, the heading time fairly advanced in both years (Table 1). These outcomes were linked to early maturation and senescence of plants because, under the HT regime, the leaf area decreased considerably (Table 1) with increasing dead-leaf dry matter (Table 2). Such phenomena are consistent with the general view of plant ontogeny (Paulsen, 1994; Redden et al., 2014). However, leaf numbers on the main stem did not differ between HT and CONT plots in either year (Table 1). These results coincided with those of a report by Yin and Kropff (1996) and indicated further that HT accelerated leaf emergence and flower initiation (Stone, 2001; Menzel and Sparks, 2006).

At harvest time, the whole-plant dry matter was less in HT plants than in CONT plants because of slender aboveground parts and poor root growth of the former (Table 2), although the tiller numbers tended to increase (+3–+7%; Table 1). Most important is the large decline of panicle dry weight (i.e. rough rice with rachis branch; −11–−35%). Partial deterioration of photosynthesis and increased respiratory loss under HT conditions might cause this decline (Peng et al., 2004; Krishnan et al., 2011). Nevertheless, the harvest index was not affected greatly by HT (Table 2). These findings suggest that overluxuriant growth was avoided in our experimental conditions, probably because of limited pot size such as 1/5000 a.

For rice, the grain numbers per panicle were lower in HT plants than in CONT plants (Table 3). Reportedly, when rice plants encountered HT such as 36°C during the neck-node differentiation to flower-bud differentiation stages, flower numbers per panicle decreased (Matsushima et al., 1964). Sterile spikelets became increasingly numerous when temperature was elevated at flowering (Oh-e et al., 2007). Drastic spikelet sterility occurred when rice plants met HT (36–38°C) at flowering, mainly because of decreased numbers of pollen grains shed on stigma (Matsui et al., 1997). HT reduced the number per panicle and % maturity of grains for the reasons described above, which reduced grain yields. Moreover, Tashiro and Wardlaw (1989) reported observation of a decrease in single grain weight with shortening of the grain growth period by HT (36–39°C) during the maturation period. Our experiments, however, demonstrated the decline of 1000-grain weight as negligible (Table 3), probably because subsistent spikelets...
grew normally and because temperatures during flowering to mid-maturation (1–20 September) were not so high (2015: HT: 28.97°C, CONT: 24.82°C, 2016: HT: 30.33°C, CONT: 26.38°C) for ‘Aichinokaori’, a late cultivar used in this experiment. If we adopted cultivars with early or medium maturation time, then their reproductive structure encountered a sufficiently higher temperature period (around early August) during the growth season than in the present study: the damage caused by high temperature might therefore be severe. In turn, the adoption of late cultivars is an alternative means of escaping from global warming, although the occurrence of extremely hot summers in the future would be unavoidable.

In conclusion, our ACRC can study the temperature and humidity effects on crop plants. Results show that HT (4°C above the outside temperature) affected some aspects of growth, yield, and yield components of rice plants, especially shortening the time to flowering. Because we adopted a late rice cultivar, the temperature of the specifically important period from flowering to mid-maturation declined considerably. It might not be crucially important for reproductive growth. Low ΔVPD treatment (between HT and CONT) during summer-autumn led to no large differences in rice plants, although further improvement must be made of humidifying-dehumidifying systems. This chamber is capable of short-period step responses of temperature and humidity and therefore, it is applicable to studies on growth promotion, yield quality improvement, physiological disorders, etc. Control of CO2 concentrations in ACRC persists as a remaining task. Probably, such control will facilitate the study of climate change effects on crop production.

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