Open-Top Chambers with Solar-Heated Air Introduction Tunnels for the High-Temperature Treatment of Paddy Fields

Masahiro Chiba¹ and Tomio Terao²

¹NARO Western Region Agricultural Research Center, NARO, 6-12-1 Nishifukatsu-cho, Fukuyama 721-8514, Japan; ²Hokuriku Research Center, NARO Agricultural Research Center, NARO, 1-2-1 Inada, Jotsu 943-0193, Japan)

Abstract: The quality of rice grain has been deteriorating as a result of the high temperature during the ripening stage caused by global warming. Easy and effective methods of high-temperature treatment are essential for the analysis of high-temperature tolerance and to screen for tolerant strains. We have improved the open-top chamber (OTC) by adding a solar-heated air introduction tunnel (SAT). The air is warmed by solar radiation as it passes through the tunnel and then flows into the OTC. The increase in temperature in the OTC-SAT was powered by solar radiation. Thereby, the temperature in OTC-SAT rose during the day according to the distance from the air intake (the nearer, the higher). A more uniform increase in temperature of approximately 1.2°C in the daytime was achieved by attaching a sloping wall and funnel-shaped air exhaust tunnel to the OTC-SAT to improve the air flow. The area of the high-temperature treatment was easily increased by increasing the width of the OTC-SAT; this finding might be useful for screening a large number of strains. The increase in the percentage of chalky grains by the use of OTC-SAT was similar to that obtained with the other treatment methods; the OTC-SAT will thus be useful for investigating high-temperature tolerance during the ripening stage, particularly in areas where the wind direction is stable. The use of an OTC with a funnel-shaped tunnel on both the air entrance and the air exit sides might be useful in areas where the wind direction is often reversed.

Key words: Chalky grain, High-temperature treatment, Paddy field, Rice (Oryza sativa L.).

The average surface temperature on earth has been increasing since the industrial revolution because of increasing CO₂ concentration and hence greenhouse effect (IPCC, 2007a). The average summer temperature in Japan rose at the rate of 1.00°C per 100 year from 1891 to 2011 because of global warming (Japan Meteorological Agency, 2012). The global warming and hence high temperature at the growing season affected the yield and quality of the crops (IPCC, 2007b).

Rice (Oryza sativa L.), the staple food in Japan, is also affected by high temperature during the ripening stage which severely damages the grain quality mainly increasing the percentage of chalky grains. The occurrence of chalky grains increases when the average temperature during 20 days after heading exceeds 26°C (Kondo et al., 2006). The increase in the fissured grains is another problem caused by temperature during 1 – 10 days after heading in rice (Nagata et al., 2004). Furthermore, the high temperature during the flowering stage increases the abundance of sterile grains and, hence, severely decreases the grain yield (Matsui et al., 2001; Mohammed and Tarpley, 2009).

Global warming will increase fluctuations in the climate (IPCC, 2012); and cold spells will still occur, although they will become less frequent (NOAA, 2010). Therefore, we need methods that can supply a high temperature to develop tolerant cultivars as well as to improve cultivation methods that may reduce the high temperature effect at the ripening stage.

There are already several methods of high-temperature treatment. The circulation of warm water (35°C) over the surface of the paddy field (Ishizaki, 2006) is one effective method of high-temperature treatment in the field. However, the initial costs and the costs of the heat source are high with this method, so it is not often used. Another problem is that this method first raises the soil and water temperatures; the air temperature rises later. The effect of the rise in root temperature has not been investigated...
intensively, and it is still not clear whether the effect of this method is the same as that of naturally high air temperature conditions.

Placing an open-sided plastic greenhouse in the paddy field (Komaki et al., 2002) is a popular method because many samples can be treated at a low cost. However, the plastic film cover reduces the solar radiation. In addition, the height of the sides of the greenhouse strongly affects the temperature, such that the panicles in higher positions are subjected to higher temperatures, and tall cultivars may be affected more.

The high-temperature treatment of covering the panicles with a plastic film tube (Terao et al., 2010) is inexpensive and can be used to compare panicles within an individual plant. However, it is difficult to treat a large number of samples with this method.

Growth chambers can be used to control the air temperature precisely, but they can be used only in studies that have clear targets because they are expensive and can treat only a small number of samples.

Heater array is a high-temperature treatment method using infrared heaters (1000 W) to the field tilting 45° horizontal and combining six of them in a hexagonal array (Kimball et al., 2008). Uniform warming was achieved across 3 m diameter plot in the daytime and nighttime. This method can be used only in the field equipped with an electrical source at more than 6000 W. The electricity cost of this heater array will be very high in high electricity cost countries such as Japan and some European countries (IEA, 2012).

The open-top chamber (OTC) is inexpensive and has a small shading effect, particularly when the sun angle is high, although the rise in temperature during the daytime is as low as 0.5°C (Chiba and Matsumura, 2006).

The high-temperature treatments that are currently in use and listed above have merits and demerits. One of the method selection criteria is whether the method uses solar radiation or other types of energy, such as fossil fuels, to raise the temperature. Although solar energy is useful only in fine weather, the running costs of solar-driven methods are cheaper than those of other methods unless there is an appropriate heat source. Therefore, we tried to develop a high-temperature treatment that used solar radiation to stably treat large numbers of samples in the field at a low cost. From this perspective, improving the OTC to enhance the temperature-increasing effect might be an easy and promising strategy.

The OTC was originally introduced to expose plants to gases, such as air pollution (Heagle et al., 1973) and was used for the study of the plant response to elevated CO₂ (Rogers et al., 1983). However, Long et al. (2005) indicated that the problem of the OTC method is in changes in environmental conditions, such as light and humidity. The decrease in radiation by the side wall of the OTC is a function of the sun angle (Olszyk et al., 1980; Drake et al., 1989; Whitehead et al., 1995; Norby et al., 1997). Additionally, there are differences in microclimatic conditions between inside and outside of the OTCs, that is, the difference in the temperature (4.3°C) and water vapor deficit (Whitehead et al., 1995; Norby et al., 1997). Although most of the OTCs aim to change gas conditions such as CO₂ concentrations without changing the air temperature, hence adopting the term “air-conditioned OTC”, our aim is to raise the temperature inside the OTC to simulate the warming conditions. Therefore, no air conditioning apparatus was added, but an apparatus to warm air by solar radiation, called solar-heated air introduction tunnel (SAT) was added to supply warm air into the OTC (OTC-SAT). The problems of side wall shading and humidity change may be partly overcome by widening the OTC or improving the air flow inside the OTC by adding SAT.

Materials and Methods

1. Location of experiment and direction of the wind

The experiment was conducted at the Hokuriku Research Center (37°7'N, 138°16'E), NARO Agricultural Research Center, National Agriculture and Food Research Organization, in Joetsu, Niigata, Japan. In this area, the sea breeze comes from the north during the day, and a land breeze from the south at night (Nakagawa and Yokoyama, 2002).

2. Experiment 1. Improvement of the OTC shape and its effect on the rise in temperature

In 2010, we equipped a paddy field with 3 types of OTC-SAT (Fig. 1, OTC-SAT-A, B, and C), and transplanted medium-size seedlings of the rice cultivar ‘Koshihikari’ on 20 May. The OTC was 4.5 m long, 1.8 m wide, and 1.4 m high, and the side was covered with plastic film (0.1 mm thick, Nobiace-mirai, Mitsubishi Plastics Agri Dream Co., Ltd., Tokyo, Japan). The SAT was attached to the north side of the OTC, i.e., the side from which the sea breeze comes. The SAT was semicircular, 1.8 m wide, 0.45 m high, and 3 m long; it was supported by an 11-mm diameter steel tunnel prop and enclosed with plastic film. The surface of the field inside of the SAT was covered with black plastic film. The OTC-SAT-A had the SAT on the air intake side, and the only other opening was on the air exhaust side. The OTC-SAT-B, contained a sloping wall made from cucumber props that was covered with plastic film, attached to the north side of the OTC to reduce the air disturbance. In OTC-SAT-C, an air exhaust tunnel was added to the south side of the OTC to improve the air flow inside of the OTC. The exhaust tunnel was 1.5 m long, 1.8 m wide, and 0.45 m high at the junction to OTC and 0.8 m high at the exhaust end.

In 2011, we set up 2 types of OTC-SAT on 22 July to test...
the suitability of the shape of the air exhaust tunnel. One was OTC-SAT-C (the same as that used in 2010), and the other was (OTC-SAT-D) having a larger air exhaust tunnel and with the same sloping wall (Fig. 1). The height of the air exhaust tunnel in OTC-SAT-D was 0.45 m at the junction to OTC and 1.4 m at the exhaust end. The tunnel was 2 m long and 1.8 m wide. We planted medium-size seedlings of the rice cultivar ‘Sasanishiki’ in OTC-SAT on 17 May. From 4 August to 9 September 2010 and from 23 July to 12 August 2011, we measured the air temperature in OTC 0.9 m above the ground and at different distances from the SAT using a temperature data logger (Thermochron SL type, KN Laboratories, Inc., Osaka, Japan) that was attached to the radiation shield housing, which was made of 5 layers of waterproof, white-painted paper dishes. The distance from the SAT to the measuring points was 0.5 m, 1.2 m, 1.9 m, 2.6 m, 3.3 m, and 4.0 m in 2010 and 0.45 m, 1.35 m, 2.25 m, 3.15 m, and 4.05 m in 2011. The temperature measuring interval was 15 min in 2010 and 20 min in 2011.

3. **Experiment 2. Expansion of the treated area and the effect on the quality of the rice grains.**

In 2011, we used OTC-SAT-CW, which was the same as OTC-SAT-C, but had an expanded width (5.4 m, three times the width of OTC-SAT-C) to increase the area for the
Table 1. Heading dates and levels of tolerance to high temperatures during ripening stage in the cultivars tested.

| Tolerance         | Cultivar      | Heading date |
|-------------------|---------------|--------------|
| Tolerant          | Fusaoiome     | 23 July      |
|                   | Tentakaku     | 24 July      |
|                   | Hanahikari    | 23 July      |
|                   | Koshijiwase   | 22 July      |
|                   | Koshiihikari  | 3 August     |
| Moderately tolerant|               |              |
| Intermediate      | Hitomebore    | 30 July      |
|                   | Haenuki       | 24 July      |
|                   | Houmenwase    | 28 July      |
| Moderately susceptible |        |              |
| Susceptible       | Todorokiwase  | 23 July      |
|                   | Koshinohana   | 23 July      |
| Sasanishiki       | 26 July       |              |

We examined the effect of this OTC-SAT on the grain quality of Sasanishiki and 13 standard rice cultivars with different levels of tolerance to heat-induced quality decline (Ishizaki, 2006). The tolerances of the 13 standard cultivars and their heading dates are listed in Table 1. Sasanishiki is susceptible or moderately susceptible according to Iwashita et al. (1973) and our previous experiment (data not shown). We planted medium-sized seedlings of the 14 cultivars in OTC-SAT-CW on 17 May and grew them until maturity. The planting density was 22.2 hills m\(^{-2}\) with 3 plants per hill. We harvested 4 hills of every cultivar at 0.45, 1.35 m, 2.25 m, 3.15 m, and 4.05 m from the SAT.

We also grew the same cultivars in a simple OTC (Fig. 1, OTC) (Chiba and Matsumura, 2006), in which warm air was not introduced in a plastic greenhouse and in a plastic film tube (Terao et al., 2010) in the same paddy field and in a natural-light growth chamber. The occurrence of chalky grains in those samples was examined in comparison with that in the other methods. The size of the OTC was 1.8 × 1.8 × 1.5 m (width × length × height) and that of the plastic greenhouse was 0.72 × 10 × 1.8 m. The side walls of the plastic greenhouse were open from 0.6 m above the ground. A total of 4 hills of each cultivar were harvested in the OTC and 5 hills in the plastic greenhouse. As controls for the high-temperature treatments (OTC-SAT-CW, OTC, and plastic greenhouse), 10 hills were harvested in the field. For the plastic tube high-temperature treatment, a tube of plastic film (A4 OHP film, PP2500, Sumitomo 3M Ltd., Tokyo, Japan) was added 3 days after heading to cover a panicle on each hill; another panicle on the same hill that had headed on the same day was selected as the control, as described in Terao et al. (2010). A total of 5 hills for each cultivar were used in the plastic film tube experiment.

For the growth chamber experiment, 3 rice seedlings were planted in a 0.02-m\(^2\) Wagner pot and grown outside until heading. When the first panicle had headed, the pots were brought into a natural-light growth chamber (Koitotron 4S-135A special type, Koito Electric Industries, Ltd., Yokohama, Japan). Two plants were grown in each pot until maturity under the control (27/22ºC day/night) or high-temperature (32/27ºC day/night) conditions. To maintain uniform light conditions among the pots, the positions of the pots were rotated every week outside and every day in the growth chamber.

Brown rice grains that were thicker than 1.8 mm were used to investigate the grain quality with an ES-1000 rice inspector (Shizuoka Seiki Co., Ltd., Shizuoka, Japan). The total number of milky white, white-belly, and immature-base grains was used as the total number of chalky grains.

4. Experiment 3. High-temperature treatment using the reverse direction wind

OTC-SAT-E was symmetrically equipped with a much larger exhaust tunnel on one side and with an air intake tunnel of the same shape on the other side (Fig. 1); we considered that this set-up might be useful in areas where the wind direction was not constant. The roles of the SAT and the air exhaust tunnel were exchanged by the wind direction. The OTC of OTC-SAT-E was 2 m wide, 1.6 m high, and 4.5 m long. The height of the large intake and exhaust tunnels was 0.45 m at the OTC side and 1.6 m at the end. The tunnels were 3 m long and 2 m wide. Medium-size seedlings of the rice cultivar ‘Sasanishiki’ were transplanted on 17 May 2011 at a density of 22.2 hills m\(^{-2}\). We measured the temperature every 20 min in the OTC and outside (control) from 31 July to 19 August, although the treatment continued until the end of August. The measurement positions were 0.6 m, 1.8 m, 3 m, and 4.2 m from the northern air intake. The rice plants from 9 hills around the thermosensor were harvested. We investigated the quality of the rice grains using the ES-1000 rice inspector without sieving. The chalky grains (the total milky white, white-belly, and immature-base grains) and dead grains (indicating very severe chalkiness) were enumerated.

5. Weather data

We used the weather data that had been measured in the research field of the Hokuriku Research Center that were provided by the Research Project of Crop Management under Climate Change to analyze the effects of solar radiation and wind on the rise in temperature in the OTC-SAT. The Automated Meteorological Data Acquisition System (AMeDAS) that records the data every hour...
The daytime (0600 – 1800) and nighttime (1800 – 0600) temperatures in OTC-SAT-A, -B, and -C at different distances from the SAT, as well as those in the corresponding positions in the control, were measured in 2010 (Fig. 2a). At 0.5 m from the SAT, the daytime temperatures in all of the OTC-SAT types were approximately 2°C higher than in the control. However, the temperature rapidly dropped with increasing distance from the SAT in OTC-SAT-A, resulting in a very small rise in temperature 4.0 m away from the SAT. This temperature gradient was slightly reduced in OTC-SAT-B, which was equipped with a sloping wall and was further reduced in OTC-SAT-C, which was equipped with a sloping wall and an air exhaust tunnel. The addition of the sloping wall and air exhaust tunnel was, therefore, effective in reducing the temperature gradient in the OTC. At night, there was no rise in temperature in any of the OTC-SATs.

The daytime temperatures in the OTC-SATs and the control in the 2011 experiment, in which we investigated the effects of increasing size of the air exhaust tunnel, are shown in Fig. 2b. The daytime temperature in OTC-SAT-C rose by as much as 2.2°C near the SAT, but the temperature elevation decreased with increasing distance from the SAT, as in the 2010 experiment. The temperature gradient patterns were almost the same as those in OTC-SAT-C in 2010 and 2011. On the other hand, the daytime temperature in OTC-SAT-D, which had a larger air exhaust tunnel, rose uniformly to approximately 1.2°C from the area near the SAT to a distance of over 3 m from the SAT. Therefore, increasing the size of the air exhaust tunnel might have helped to flatten the gradient. As in 2010, the nighttime temperature of the OTC-SATs did not increase in 2011. These results indicate that OTC-SAT-D, which was equipped with a sloping wall and large air exhaust tunnel, was useful for evening out the rise in temperature.

Fig. 2 shows an example of the diurnal variation of the air temperature in OTC-SAT-C in 2011 at different distances from the air intake. The temperatures in the OTC during the daytime were highest at 0.45 m, followed by 1.35 m, 2.25 m, and 3.15 m, and lowest at 4.05 m. Although the temperature at 4.05 m was the lowest, it was still higher than that of the control. The temperature in the OTC during the nighttime was the same as that of the control.

2. Effect of solar radiation intensity and wind speed on the rise in temperature in the OTC-SAT

To evaluate the effect of solar radiation on the rise in temperature in the OTC-SAT, we analyzed the relationship (hourly) from the Japan Meteorological Agency (http://www.data.jma.go.jp/obd/stats/etrn/index.php) to analyze the wind direction in August in the major cities of every prefecture of Japan to evaluate the areas of Japan where the OTC-SAT would be usable.

Results

1. The rise in temperature in the OTC-SAT

The daytime (0600 – 1800) and nighttime (1800 – 0600) temperatures in OTC-SAT-A, -B, and -C at different distances from the SAT, as well as those in the corresponding positions in the control, were measured in 2010 (Fig. 2a). At 0.5 m from the SAT, the daytime temperatures in all of the OTC-SAT types were approximately 2°C higher than in the control. However, the temperature rapidly dropped with increasing distance from the SAT in OTC-SAT-A, resulting in a very small rise in temperature 4.0 m away from the SAT. This temperature gradient was slightly reduced in OTC-SAT-B, which was equipped with a sloping wall and was further reduced in OTC-SAT-C, which was equipped with a sloping wall and an air exhaust tunnel. The addition of the sloping wall and air exhaust tunnel was, therefore, effective in reducing the temperature gradient in the OTC. At night, there was no rise in temperature in any of the OTC-SATs.

The daytime temperatures in the OTC-SATs and the control in the 2011 experiment, in which we investigated the effects of increasing size of the air exhaust tunnel, are shown in Fig. 2b. The daytime temperature in OTC-SAT-C rose by as much as 2.2°C near the SAT, but the temperature elevation decreased with increasing distance from the SAT, as in the 2010 experiment. The temperature gradient patterns were almost the same as those in OTC-SAT-C in 2010 and 2011. On the other hand, the daytime temperature in OTC-SAT-D, which had a larger air exhaust tunnel, rose uniformly to approximately 1.2°C from the area near the SAT to a distance of over 3 m from the SAT. Therefore, increasing the size of the air exhaust tunnel might have helped to flatten the gradient. As in 2010, the nighttime temperature of the OTC-SATs did not increase in 2011. These results indicate that OTC-SAT-D, which was equipped with a sloping wall and large air exhaust tunnel, was useful for evening out the rise in temperature.

Fig. 3 shows an example of the diurnal variation of the air temperature in OTC-SAT-C in 2011 at different distances from the air intake. The temperatures in the OTC during the daytime were highest at 0.45 m, followed by 1.35 m, 2.25 m, and 3.15 m, and lowest at 4.05 m. Although the temperature at 4.05 m was the lowest, it was still higher than that of the control. The temperature in the OTC during the nighttime was the same as that of the control.
between the total solar radiation and daytime rise in temperature in OTC-SAT-C and -D (Fig. 4a and b, respectively). The daytime rise in temperatures in OTC-SAT-C and -D were positively and significantly correlated with the solar radiation, except at 2.25 m from the SAT of OTC-SAT-C. In OTC-SAT-C, the regression line at 0.45 m was far higher and the slope much steeper than at the other measuring points, indicating that the rise in temperature near the SAT was severely affected by the intensity of solar radiation. In contrast, the regression lines were much closer and the slopes were similar to those at other measuring points in OTC-SAT-D, showing that a similar rise in temperature is reached further away. However, this positive correlation between the solar radiation and the rise in temperature seems to depend on the inclusion of the data with low solar radiation. If the solar radiation data less than 10 MJ m\(^{-2}\) d\(^{-1}\) were omitted, the positive correlation would disappear (dotted regression lines).

![Diurnal temperature variations in OTC-SAT-C in 2011. The values at 0.45 m, 1.35 m, 2.25 m, 3.15 m, and 4.05 m from the SAT. The temperature was average of 23 July to 12 August.](image)

![Relationship between the solar radiation and the daytime rise in temperature in OTC-SAT-C (a) and OTC-SAT-D (b) and between the hourly records of the solar radiation and the concurrent rise in temperature from 0900 to 1500 in OTC-SAT-C (c) and OTC-SAT-D (d), at which time the wind blew from the quarter around north in 2011. Data at 0.45 m, 2.25 m, and 4.05 m from the SAT were plotted. *, ** and *** indicate significant correlations at the 5%, 1%, and 0.1% levels, respectively. The solid lines in a and b are the regression lines of all of the data, and the dotted lines are those excluding the data of days with less than 10 MJ m\(^{-2}\) d\(^{-1}\) solar radiation.](image)
Fig. 4c and d show the relationship between the hourly records of solar radiation and the concurrent rise in temperature from 0900 to 1500 when wind blew from the quarter sector around north. This relationship is similar to that of the daily records: the higher the hourly solar radiation, the greater the rise in temperature. However, the rise in temperature also seems to be saturated at the radiation higher than 2 or 2.5 MJ m\(^{-2}\) hr\(^{-1}\).

To evaluate the effect of wind speed on the rise in temperature in the OTC-SAT, we analyzed the relationship between the wind speed and the rise in temperature using the hourly data of wind speed that were averaged for 10 min before that hour and the concurrent temperature from 0900 to 1500 in OTC-SAT-C and -D in 2011 (Fig. 5). When the solar radiation was less than 2.5 MJ m\(^{-2}\) hr\(^{-1}\), the temperature rose with the increasing wind speed (Fig. 5a and b). This correlation between the rise in temperature and wind speed might be caused by the difference in the solar radiation. Fig. 5e shows the relationship between the solar radiation and wind speed. The wind speed was positively correlated with the solar radiation. Analysis of the

Fig. 5. Relationship between the wind speed and the rise in temperature in OTC-SAT-C and OTC-SAT-D in 2011 at 0.45 m, 2.25 m, and 4.05 m from the SAT, and that between the solar radiation and the wind speed (average of 10 min before the hour).

*, **, and *** indicate significant correlations at the 5%, 1%, and 0.1% levels, respectively. The data were obtained when the wind blew from the quarter sector around north from 0900 to 1500 on 26 July to 12 August. Low solar radiation is less than 2.5 MJ m\(^{-2}\) hr\(^{-1}\) and high solar radiation is 2.5 MJ m\(^{-2}\) hr\(^{-1}\) or more.
1. **Correlation between the rise in temperature and the wind speed under high solar radiation**

At a high solar radiation (2.5 MJ m$^{-2}$ hr$^{-1}$ or more), the rise in temperature seemed saturated (Fig. 4c and d) and decreased with increasing wind speed (Fig. 5c and d).

2. **Expansion of the OTC width and its effect on the grain quality: comparison with other treatment methods**

To increase the treatment area, we tripled the width of OTC-SAT-C and created OTC-SAT-CW. We measured the daytime temperatures at different distances from the SAT in the east, middle, and west rows of the OTC-SAT-CW (Fig. 6). All 3 rows showed almost identical patterns in which the temperature decreased with increasing distance from the SAT.

Standard cultivars differing in tolerance to high temperatures during the ripening stage (Ishizaki, 2006) were grown in OTC-SAT-CW in 2011, and the occurrence of chalky grains was measured (Fig. 7). The figure shows the chalky grain percentages of tolerant (Fusaotome), moderately tolerant (average of Tentakaku, Hanahikari, Koshijiwase, and Koshihikari), intermediate (average of Hitomebore, Haenuki, and Hounenwase), moderately susceptible (average of Ajikodama, Kagahikari, and Ougiwase), and susceptible (average of Todorokiwase and Koshinohana) cultivars at different distances from the SAT.

Although the differences among the cultivars decreased with increasing distance from the SAT, the tolerant strains consistently had a lower percentage of chalky grain. These standard cultivars were selected by averaging the percentages of chalky grains determined by several methods (Ishizaki, 2006). The OTC-SAT will screen a
group of tolerant strains similar to those selected by averaging the results obtained by other methods.

We evaluated the effects of the high-temperature treatment using OTC-SAT-CW, the OTC, the plastic greenhouse, the plastic film tube, and the growth chamber in 13 standard cultivars and Sasanishiki. The relationship between the rise in temperature and the chalky grain percentage is shown in Fig. 8. The temperature was not measured in the plastic film tube and was, therefore, omitted from the statistical analysis. There was a linear relationship between the daytime temperature and the average chalky grain percentage (Fig. 8a). However, the increase in the chalky grain percentage with the rise in temperature in the growth chamber was slightly lower than that in the other methods. We examined the effect of the nighttime temperature on the percentage of chalky grains (Fig. 8b). Although the nighttime temperatures (except for those in the growth chamber) were almost the same as in the control, the percentage of chalky grains increased with the rise in daytime temperature.

We calculated the coefficients of correlation of the increase in chalky grains relative to the control in each treatment with those in other treatments (Table 2). The correlation coefficients among values in OTC-SAT-CW (CW1 – 5), OTC, plastic greenhouse, and plastic film tube were significant. However, the coefficients of correlation of the value in the growth chamber with that in other methods (except for OTC-SAT-CW3, OTC-SAT-CW5, and the OTC) were not significant.

### Table 2. Correlation coefficient matrix of the increased chalky grain percentage in each treatment with those in the other high-temperature treatment methods.

|                | OTC-SAT-CW2 | OTC-SAT-CW3 | OTC-SAT-CW4 | OTC-SAT-CW5 | OTC | Plastic greenhouse | Plastic film tube | Growth chamber |
|----------------|-------------|-------------|-------------|-------------|-----|-------------------|-------------------|-----------------|
| OTC-SAT-CW1    | 0.822***    | 0.849***    | 0.626*      | 0.701**     | 0.656* | 0.901***          | 0.702***          | 0.486           |
| OTC-SAT-CW2    | 0.847***    | 0.730***    | 0.845***    | 0.786***    | 0.767** | 0.713***          | 0.628***          | 0.528           |
| OTC-SAT-CW3    | 0.847***    | 0.898***    | 0.879***    | 0.820***    | 0.686** | 0.626**           | 0.660***          | 0.364           |
| OTC-SAT-CW4    | 0.849***    | 0.888***    | 0.720**     | 0.792***    |         |                   |                   |                 |
| OTC-SAT-CW5    |             | 0.966***    |             |             | 0.777** | 0.769**           |                   | 0.657*          |
| OTC            |             |             |             |             | 0.769** | 0.823***          | 0.571*            |                 |
| Plastic greenhouse |             |             |             |             |         |                   |                   | 0.465           |
| Plastic film tube |             |             |             |             |         |                   |                   | 0.190           |

OTC-SAT-CW1, -CW2, -CW3, -CW4, and -CW5 were 0.45, 1.35, 2.25, 3.15, and 4.05 m, respectively, away from SAT. *, **, and *** indicate a significant correlation at the 5%, 1%, and 0.1% levels, respectively. Sasanishiki and 13 standard cultivars that were tolerant to high temperatures during the ripening stage were investigated.

4. **OTC-SAT adaptable to the reversed wind direction**

OTC-SAT-D, and most likely OTC-SAT-DW, may be useful in areas where the daytime wind direction is uniform. However, the wind direction often changes. For example, the wind direction in Joetsu is usually from the north, but at the time of the foehn wind it is reversed. To improve the OTC-SAT to adapt to winds from different directions, we developed the symmetrically designed OTC-SAT-E (Fig. 1), which can be used in winds from opposing directions. The larger air exhaust tunnel effectively decreased the temperature gradient in OTC-SAT-D. Therefore, OTC-SAT-E had a much larger exit as an air introduction tunnel on both sides to collect more air. The daytime temperature in OTC-SAT-E is shown in Fig. 9. The daytime temperature gradient from the air intake to the exit was eliminated, but the temperature at the point near the air intake, did not increase so much as at other points. The percentage of chalky grains increased at the center of OTC-SAT-E. However, the percentage of dead grains was higher near the air intake. As in the other OTC-SATs, the nighttime temperature was the same as in the control.

### Discussion

1. **Effect of the OTC-SAT and improvement of its temperature gradient**

To develop a high-temperature treatment method that used solar radiation to stably treat large numbers of samples in the field at a low cost, we improved the simple form of the OTC (Fig. 1), which was surrounded by plastic film by attaching an SAT that may raise the temperature of air passing through and air exit to flow through the warmed air was attached. In addition, the length of the OTC was increased to 4.5 m to evaluate the effect of air flow compared to the 1.8 m square OTC. In the basic type of OTC-SAT (OTC-SAT-A) that had only the SAT but not the specific exit exhibited a high daytime temperature near the SAT, but it declined rapidly with increasing distance from the SAT (Fig. 2). Adding a sloping wall (OTC-SAT-B in Fig. 1) slightly decreased the temperature gradation compared to that of OTC-SAT-A, but the effect was not satisfactory. Adding an air exhaust tunnel (OTC-SATC) effectively decreased the temperature gradient, but
additional improvement was necessary.

In 2011, we increased the size of the air exhaust tunnel to decrease the daytime temperature gradient (OTC-SAT-D). As a result, the daytime temperature gradient was further reduced and, although a slight gradient remained, an almost uniform rise in temperature of approximately 1.2°C from the area near the SAT to a distance of over 3 m from the SAT was achieved. Although the area of uniform rise in temperature was not expanded to 4.5 m, this is practical. The optimum size of the exhaust tunnel was not investigated, but a more even rise in temperature might be obtained by increasing the size of exhaust exit.

Increasing the size of the tunnel in both sides of the OTC (OTC-SAT-E) resulted in a center-peaked temperature distribution as well as the occurrence of a chalky grain distribution. It seems that the temperature gradient from the inlet of air to the exhaust side had been eliminated, but because of the large opening, the outside air could be exchanged more easily near both sides of OTC and, therefore, decreased the air temperature in those locations. It might be necessary to narrow the opening of the tunnel near the OTC to optimize the air flow and thus establish a uniform rise in temperature. In contrast to the chalky grains, the percentage of dead grains (the most severe manifestation of high-temperature damage) increased near the air intake. The reason for this increase is not clear, but it may be due to the temporary but severe rise in temperature that occurred near the air intake. These temperature surges might have occurred because more time was taken for the slow winds to pass through the tunnel. The OTC-SATE design should have the same effect if the wind direction is reversed and is thus theoretically useful in such areas, although we had no chance to investigate the effects of an opposing wind direction.

The linear gradient of daytime temperatures in OTC-SAT-A and -B from air intake to exhaust was similar to that in the temperature gradient chamber (TGC), which is used to estimate the effects of different degrees of temperature increases on the rice quality (Tsukaguchi and Iida, 2008). Therefore, an OTC-SAT without a sloping wall or air exhaust tunnel is as useful as a TGC for investigating the effects of various temperatures on the rice quality.

2. Expansion of the treatment area in the OTCSAT and its effect on the light condition

We expanded the width of OTC-SAT-CW to 3 times the width of OTC-SAT-C to increase the treatment area. This width expansion did not affect the temperature profile inside of the OTC and, thereby, the treatment area might be expanded (Fig. 6). Also the increase in the width of the OTC would reduce the shading effect that is caused by the presence of the side walls. The shading effect of the side wall is the main problem of the OTC (Olszyk et al., 1980; Drake et al., 1989; Whitehead et al., 1995; Norby et al., 1997). This effect was not negligible even if the diameter of the OTC was approximately 2 m (Heagle et al., 1973; Collins et al., 1995; Long et al., 2005), but the percentage of shaded areas might be reduced if the width of the OTC is increased to 5.4 m or more. It is very likely that using a wider version of OTC-SAT-D (OTC-SAT-DW) would increase the treatment area with the uniform pattern of rise in temperature and would be promising for the high-temperature treatment of wide areas.

3. The effect of the rise in temperature by solar radiation intensity

The temperature in the OTC-SAT is raised by solar
radiation. Thereby, the extent of the rise in temperature is increased by the increasing solar radiation (Fig. 4). When the daily solar radiation was less than 10 MJ m$^{-2}$ d$^{-1}$ on cloudy or rainy days, the temperature in the OTC-SATs did not rise, and when it was approximately 15 MJ m$^{-2}$ d$^{-1}$ or more, the temperature rose. Additionally, a similar relationship was observed in the hourly record of solar radiation and rise in temperature. The rise in temperature seems to saturate at 2.0 – 2.5 MJ m$^{-2}$ hr$^{-1}$ solar radiation. This apparent saturation of the rise in temperature is due to warm air escaping from the upper opening of the OTC-SATs. This saturation showed that the temperature in the OTC-SATs is sufficiently increased if the amount of the solar radiation is higher than 15 MJ m$^{-2}$ d$^{-1}$, that is more than 60% of full radiation.

4. Humidity and wind in the OTC-SAT

Another problem with the OTC might be the effect of the turbulence of the air flow by the side wall on the water vapor deficit (Whitehead et al., 1995; Norby et al., 1997). Dabros et al. (2010) revealed that the absolute humidity at the time of maximum temperature in an OTC was set in a transitional mixed wood forest was higher than that in the control during summer. We did not measure the humidity and wind speed inside the chamber. However, our OTC-SATs were set in paddy field covered with water, which may supply humidity to the plants grown both inside and outside of the OTC-SAT. Additionally, the wind can pass through easily inside the chamber. Thereby, the inside environment of our air flow-type OTC-SAT is less isolated compared to the authentic OTC, which has a completely covered side wall. The effect of wind speed in our research field on the rise in temperature in the OTC-SAT was evaluated in Fig. 5. When the solar radiation was less than 2.5 MJ m$^{-2}$ hr$^{-1}$, a stronger wind seems to raise the temperature more. However, this rise seems to be an artifact that is caused by the positive correlation between the wind speed and the solar radiation; the higher solar radiation caused both the wind speed increase and the rise in temperature (Fig. 5e). When the solar radiation was 2.5 MJ m$^{-2}$ hr$^{-1}$ or more, strong enough to saturate the rise in temperature, the rise in temperature seems to be negatively correlated with the wind speed (Fig. 5). A higher speed wind may pass through the SAT rapidly; therefore, the rise in temperature is considered to be low if the effect of solar radiation is the same. This negative correlation of the wind speed with the rise in temperature suggests that enough air flew inside of the OTC-SAT.

When the CO$_2$ concentration inside the OTC is not controlled, the decrease in the daytime CO$_2$ concentration in the OTC might be another problem that may lower the quality of the rice grains. Although we did not measure the CO$_2$ concentration inside the OTC-SAT, its decrease in the OTC-SATs is considered to be less than that in the authentic 2-m diameter OTC that is surrounded by plastic film (Heagel et al., 1973; Collins et al., 1995; Long et al., 2005) due to the continuous air flow.

5. Effect of the rise in temperature in the OTC-SAT on the quality of the rice grains

We examined the effect of the OTC-SAT-CW on the quality of the rice cultivars using the standard cultivars differing in high-temperature tolerance (Ishizaki, 2006) in comparison with that of other high-temperature treatment methods (the OTC, the plastic greenhouse, the plastic film tube, and the growth chamber). Although those treatment methods, except for the growth chamber, raised the temperature only in the daytime, the percentage of chalky grains was increased. In addition, there was a linear relationship between the daytime temperature and the average chalky grain percentage (Fig. 8a). Morita et al. (2002, 2004) revealed that the rice grain quality was affected by either the daytime temperature or the nighttime temperature during ripening. Our results show that the high daytime temperature is important for the degradation of the rice grain quality regardless of the nighttime temperature. Thereby, the high-temperature treatment using the OTC-SAT is usable even if the nighttime temperature is not raised. This result is similar to that of Terao et al. (2010) in which the plastic film tube increased only the daytime temperature and was still effective in decreasing the grain quality.

We calculated the coefficients of the correlation of the chalky grain increase relative to the control in each treatment with those in the other high-temperature treatments (Table 2). There were significant correlations among the values in OTC-SAT-CW, the OTC, the plastic greenhouse, and the plastic film tube. However, the correlation coefficients between the values in the growth chamber and those in the other treatments were small. There are three possible reasons why the effects of the growth chamber differed from the others. The first is the difference in cultivation methods: in the growth chamber, the rice plants were grown in Wagner pots, whereas in the other treatments, they were grown in a paddy field. The second is the difference in the temperature fluctuation: there were uniform daytime and nighttime temperatures in the growth chamber, whereas there were natural fluctuations in the field. The third is that the nighttime temperature rose only in the growth chamber.

A close correlation between the percentage of chalky grains in the OTC-SAT and other treatments, except for the growth chamber and between the high-temperature tolerance of cultivars and their response to OTC-SAT-CW treatment (Fig. 7), showed that the OTC-SAT is as useful as the other methods, including those using a heat source other than solar radiation.
Table 3. Percentage frequencies of the wind direction at 47 AMeDAS points in the major cities of every prefecture and Takada in August 2010 – 2012.

| AMeDAS point | Most frequent wind direction | A: Frequency of wind from most frequent quartar sector (%) | B: Frequency of wind from quarter sector opposite A (%) | C: Frequency of other winds, including windless conditions (%) |
|--------------|-------------------------------|--------------------------------------------------------|--------------------------------------------------------|----------------------------------------------------------|
| Tsu          | ESE                           | 80.2                                                   | 9.5                                                    | 10.3                                                    |
| Sendai       | SE                            | 78.6                                                   | 6.3                                                    | 15.1                                                    |
| Maebashi     | ESE                           | 71.4                                                   | 11.7                                                   | 16.9                                                    |
| Tokushima    | SE                            | 69.7                                                   | 7.1                                                    | 23.2                                                    |
| Wakayama     | WSW                           | 69.4                                                   | 7.2                                                    | 23.3                                                    |
| Kochi        | SE                            | 68.5                                                   | 4.0                                                    | 27.5                                                    |
| Hiroshima    | SSW                           | 67.9                                                   | 10.9                                                   | 21.2                                                    |
| Tokyo        | SSE                           | 66.4                                                   | 10.4                                                   | 23.2                                                    |
| Chiba        | WSW                           | 64.7                                                   | 17.8                                                   | 17.5                                                    |
| Morioka      | S                             | 64.0                                                   | 9.0                                                    | 27.0                                                    |
| Utsunomiya   | SE                            | 63.4                                                   | 6.9                                                    | 29.6                                                    |
| Shizuoka     | S                             | 61.6                                                   | 5.9                                                    | 32.5                                                    |
| Yamaguchi    | SE                            | 60.8                                                   | 4.8                                                    | 34.4                                                    |
| Takada       | N                             | 60.5                                                   | 15.4                                                   | 24.1                                                    |
| Toyama       | NNE                           | 59.9                                                   | 17.7                                                   | 22.4                                                    |
| Kobe         | SW                            | 59.9                                                   | 9.7                                                    | 30.4                                                    |
| Yokohama     | SW                            | 59.3                                                   | 9.5                                                    | 31.2                                                    |
| Miyazaki     | E                             | 59.3                                                   | 26.4                                                   | 14.3                                                    |
| Aomori       | N                             | 58.8                                                   | 4.0                                                    | 37.2                                                    |
| Okayama      | ESE                           | 58.1                                                   | 9.4                                                    | 32.6                                                    |
| Akita        | WSW                           | 57.9                                                   | 8.9                                                    | 33.2                                                    |
| Nagoya       | SSE                           | 56.1                                                   | 15.8                                                   | 28.1                                                    |
| Nagasaki     | SW                            | 54.8                                                   | 15.4                                                   | 29.8                                                    |
| Kofu         | SW                            | 54.5                                                   | 7.1                                                    | 38.4                                                    |
| Gifu         | SSW                           | 54.3                                                   | 9.9                                                    | 35.8                                                    |
| Matsuyama    | NW                            | 53.6                                                   | 9.1                                                    | 37.3                                                    |
| Naha         | E                             | 51.8                                                   | 5.7                                                    | 42.5                                                    |
| Mito         | E                             | 51.6                                                   | 7.4                                                    | 40.9                                                    |
| Kagoshima    | SSE                           | 50.5                                                   | 5.1                                                    | 44.4                                                    |
| Kumamoto     | SW                            | 50.0                                                   | 15.5                                                   | 34.5                                                    |
| Yamagata     | N                             | 48.5                                                   | 13.8                                                   | 37.7                                                    |
| Takamatsu    | ENE                           | 47.9                                                   | 17.4                                                   | 34.7                                                    |
| Sapporo      | SSE                           | 47.3                                                   | 25.3                                                   | 27.3                                                    |
| Osaka        | WSW                           | 47.3                                                   | 30.9                                                   | 21.8                                                    |
| Matsue       | W                             | 46.1                                                   | 37.8                                                   | 16.1                                                    |
| Saga         | ENE                           | 45.0                                                   | 8.9                                                    | 46.1                                                    |
| Saitama      | S                             | 44.2                                                   | 18.4                                                   | 37.3                                                    |
| Kanazawa     | N                             | 43.3                                                   | 1.7                                                    | 55.0                                                    |
| Oita         | N                             | 42.4                                                   | 15.8                                                   | 41.8                                                    |
| Tottori      | S                             | 42.2                                                   | 39.6                                                   | 18.1                                                    |
| Fukui        | NNW                           | 41.8                                                   | 29.6                                                   | 28.6                                                    |
| Fukushima    | N                             | 40.5                                                   | 34.9                                                   | 24.6                                                    |
| Fukushima    | S                             | 40.1                                                   | 16.7                                                   | 43.2                                                    |
| Nagano       | SW                            | 39.9                                                   | 26.0                                                   | 34.1                                                    |
| Nara         | NE                            | 39.9                                                   | 26.4                                                   | 33.6                                                    |
| Kyoto        | E                             | 39.6                                                   | 14.7                                                   | 45.6                                                    |
| Otsu         | NW                            | 39.3                                                   | 27.5                                                   | 33.2                                                    |
| Niigata      | NNW                           | 37.5                                                   | 26.3                                                   | 36.3                                                    |

The AMeDAS points were listed in the order of the values of A.
6. Areas where the OTC-SAT will be usable

OTC-SAT-D/DW was designed for areas where the wind direction is relatively stable in the daytime. To examine the areas in Japan where OTC-SAT-D/DW would be usable, we analyzed the wind direction in August in the major cities in every prefecture of Japan over 3 years (2010 – 2012) using AMeDAS hourly records from 0900 to 1500. Table 3 shows the most frequent wind direction in 16-point compass format; the percentage frequency the wind blew from the quarter that included the most frequent wind direction (A); the percentage frequency of the opposite quarter (B); and the percentage frequency of the other winds including windless conditions (C). The sampling points were listed in the order of A values. The higher the value of A, the more the OTC-SAT-D/DW would be useful at that point. OTC-SAT-D/DW would definitely be suitable for use at points with A values higher than that at Takada which is the AMeDAS point nearest to the farm where we performed this research (Table 3). These OTCs might also be useful at points with A values that are slightly lower than at that Takada if their B or C values are not high. These OTCs might not be suitable at points with high C values, such as Saga, Kanazawa, Fukushima, and Kyoto. However, OTC-SAT-E might be useful at points with high B values, such as at Tottori and Matsue, although the fine-tuning of this technique is needed. The wind direction is affected by local landforms; hence the values in major cities may not be applicable to surrounding areas, even within the same prefecture. Before the OTC-SAT is introduced, the local wind direction should be investigated using the nearby AMeDAS points to evaluate the suitability of the OTC or to determine the type of OTC required.

7. Conclusion

In this study, we developed a high-temperature treatment method (OTC-SAT) that introduces warm air heated by solar radiation into the open-top chamber (OTC). The OTC-SAT raised the temperature only in the day and not at night. Other merits and demerits of OTC-SAT compared to other methods are as summarized in Table 4. If the wind condition is well matched, OTC-SAT will provide relatively stable and efficient temperature elevation with very few shading effect areas at a low cost. It will be usable to screen high temperature tolerant strains in the field conditions as well as to evaluate the effect of elevated temperature on the crop production or to evaluate the cultivation methods to minimize the effect of elevated temperature.

Acknowledgments

We thank Mr. S. Kitagawa of NARO Kyushu Okinawa Agricultural Research Center; Dr. T. Hirose and Dr. M. Furuhata of Hokuriku Research Center, NARO Agricultural Research Center (NARC); and Dr. K. Nagata of NARO Western Region Research Center for their valuable advice. We are also grateful to Mr. T. Kotake, Mr. Y. Maruyama, Mr. T. Genba, Mr. K. Yazaki, Mr. S. Saito, and Mr. K. Koide of Hokuriku Research Center, NARC, for their excellent technical support of the field work, and Ms. K. Nozaki, Ms. S. Hayashi, and Ms. N. Sugiyama for their excellent technical support of this research. We are also grateful to Dr. Y. Kominami of the Research Project of Crop Management under Climate Change, Hokuriku Research Center, NARC, for providing weather data.

References

Chiba, M. and Matsumura, O. 2006. High temperature treatment for rice in paddy field by breaking wind. Jpn. J. Crop Sci. 75 (Extra 1): 228-229**.
Collins, L.B., Jones, P.H., Ingram K.T. and Pamplona, R.C. 1995. Open-top chambers for field studies of rice response to carbon dioxide and temperature: system design. In S. Peng, K.T. Ingram, H.U. Neue and L.H. Ziska eds., Climate Change and Rice. Springer, Berlin. 232-243.
Dabros, A., Fyles, J.W. and Strachan, I.B. 2010. Effects of open-top chambers on physical properties of air and soil at post-disturbance sites in northwestern Quebec. Plant Soil 333: 203-218.

Table 4. Features of OTC-SAT and other high-temperature treatment methods.

| High-temperature treatment method | Cost | Stability of effect | The number of treated sample | Avoidance of Shading | The effect of wind | Remarks |
|----------------------------------|------|---------------------|-----------------------------|----------------------|-------------------|---------|
| Circulation of warm water        | P    | G                   | G                           | E-N                  | G                 | Mainly used for breeding, shading near border |
| Prastic green house              | G    | N                   | E                           | P                    | P                 | Unstable treatment temperature, effect of shade |
| Growth chamber                   | P    | E                   | P                           | N                    | E                 | Unusable at field |
| Plastic film tube                | E    | N                   | P                           | E                    | G                 | For comparison in an individual |
| Open top chamber                 | G    | P                   | N                           | G                    | N                 | Low efficiency, change in moisture and CO₂ concentration |
| Heater array                     | P    | G                   | N                           | E                    | N                 | Need large electric source near the field |
| OTC-SAT                          | G    | G                   | E                           | E-N                  | G-P*              |         |

E: Excellent, G: Good, N: Normal, P: Poor.
†: Depend on the wind conditions at the location.
Drake, B.G., Leadley, P.W., Arb, W.J., Nasir, D. and Curtis, P.S. 1989. An open top chamber for field studies of elevated atmospheric CO₂ concentration on saltmarsh vegetation. *Functional Ecol.* 3: 363-371.

Heagle, A.S., Body, D.E. and Heck, W.W. 1973. An open-top field chamber to assess the impact of air pollution on plants. *J. Environ. Qual.* 2: 365-368.

IEA 2012. Energy prices and taxes, 4th quarter 2012. [Online]. Available at http://www1.ncdc.noaa.gov/pub/data/cmb/bams-bj&ML.KOB=696373432929 (accessed 26 September 2013, verified 17 December 2013).

IPCC 2007b. Climate change 2007: Working group II: Impacts, adaptation and vulnerability. [Online]. Available at http://www.ipcc.ch/publications_and_data/ar4/wg2/en/contents.html (accessed 25 March 2013, verified 17 December 2013).

IPCC 2007b. Climate change 2007: Working group II: Impacts, adaptation and vulnerability. [Online]. Available at http://www.ipcc.ch/publications_and_data/ar4/wg2/en/contents.html (accessed 25 March 2013, verified 17 December 2013).

IPCC 2002a. Climate change 2001: The physical science basis. [Online]. Available at http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html (accessed 25 March 2013, verified 17 December 2013).

IPCC 2002b. Climate change 2001: Impacts, adaptation and vulnerability. [Online]. Available at http://www.ipcc.ch/publications_and_data/ar4/wg2/en/contents.html (accessed 25 March 2013, verified 17 December 2013).

IPCC 2002b. Climate change 2001: Impacts, adaptation and vulnerability. Special report. [Online]. Available at http://www1.ncdc.noaa.gov/pub/data/cmb/bams-bj&ML.KOB=696373432929 (accessed 26 September 2013, verified 17 December 2013).

Ishizaki, K. 2006. Evaluation of various screening systems for high grain quality in rice cultivars under high-temperature grain-filling conditions, and the selection of their standard cultivars. *Jpn. J. Crop Sci.* 75: 502-506***.

Iwashita, T., Shinya, A., Yamakawa, Y., Doi, O., Uehara, Y. and Toriyama, K. 1973. High temperature ripening of rice plants—Change in the quality of rice grains and difference among cultivars—. *Rep. Kyushu Branch Crop Sci. Soc. Jpn.* 39: 48-57***.

Japan Meteorological Agency 2012. Climate change monitoring report 2011. [Online]. Available at http://www.data.kishou.go.jp/climate/cplinfo/monitor/2011/pdf/ccmr2011_all.pdf (accessed 25 March 2013, verified 17 December 2013)***.

Kimball, B.A., Conley, M.M., Wang, S., Lin, X., Luo, C., Morgan, J. and Smith, D. 2008. Infrared heater arrays for warming ecosystem field plots. *Global Change Biol.* 14: 309-320.

Komaki, Y., Sasahara, H. and Uehara, Y. 2002. Varietal differences of ripening ability among early-maturing rice varieties under high temperature in a vinyl house. *Hokuriku Crop Sci.* 37: 12-16**.

Kondo, M., Morita, S., Nagata, K., Koyama, Y., Ueno, N., Hosoi, J., Ishida, Y., Yamakawa, T., Nakayama, Y., Yoshioka, Y., Ohashi, Y., Iwai, M., Odaira, Y., Nakatsu, S., Katsuba, Z., Hajima, M., Mori, Y., Kimura, H. and Sakata, M. 2006. Effects of air temperature during ripening and grain protein contents on grain chalkiness in rice. *Jpn. J. Crop Sci.* 75 (Extra 2): 14-15**.

Long, S.P., Ainsworth, E.A., Leakey, A.D.B. and Morgan, P.B. 2005. Global food insecurity. Treatment of major food crops with elevated carbon dioxide or ozone under large-scale fully open-air conditions suggests recent models may have overestimated future yields. *Philos. Trans. R. Soc. London, Ser. B.* 360: 2011-2020.

Matsui, T., Omasa, K. and Horie, T. 2001. The difference in sterility due to high temperatures during the flowering period among japonica-rice varieties. *Plant Prod. Sci.* 4: 90-93.

Mohammed, A.R., Tarpley, L. 2009. High nighttime temperatures affect rice productivity through altered pollen germination and spikelet fertility. *Agric. For. Meteorol.* 149: 999-1008.

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. *Ipn. J. Crop Sci.* 71: 102-109**.

Morita, S., Shiratsuchi, H., Takahashi, J. and Fujita, K. 2004. Effect of high temperature on grain ripening in rice plants—Analysis of the effects of high night and high day temperatures applied to the panicle and other parts of the plant. *Ipn. J. Crop Sci.* 73: 77-83***.

Nagata, K., Takita, T., Yoshinaga, S., Terashima, K. and Fukuda, A. 2004. Effect of air temperature during the early grain-filling stage on grain fissuring in rice. *Ipn. J. Crop Sci.* 73: 336-342**.

Nakagawa, K. and Yokoyama, K. 2002. Local climate and climate change in Joetsu area. In *The editorial committee of the history of Joetsu city ed., The Book of Materials Part 1; Nature, The History of Joetsu.* Joetsu City Government, Joetsu. 255-257***.

Norby, R., Edwards, N., Riggs, J., Abner, C., Wullschleger, S. and Gunderson, C. 1997. Temperature-controlled open-top chambers for global change research. *Global Change Biol.* 3: 259-267.

NOAA 2010. State of the climate in 2009. Highlights. [Online]. Available at http://www1.ncdc.noaa.gov/pub/data/cmb/bams-sotc/2009/bams-sotc-2009-brochure-lo-rez.pdf (accessed 20 May 2013, verified 17 December 2013).

Olszyk, D.M., Tibbits, T.W. and Hertzberg, W.M. 1980. Environment in open-top field chambers utilized for air pollution studies. *J. Environ. Qual.* 9: 610615.

Rogers, H.H., Heck, W.W. and Heagle, A.S. 1983. A field technique for the study of plant responses to elevated carbon dioxide concentrations. *J. Air Pollut. Control Assoc.* 33: 42-44.

Terao, T., Chiba, M. and Hirose, T. 2010. A simple equipment to screen the rice strains tolerant to high temperature in the ripening processes. *Ipn. J. Crop Sci.* 79: 166-173***.

Tsukaguchi, T. and 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 Prod. Sci.* 11: 203-210.

Whitehead, D., Hogan, K.P., Rogers, G.N.D., Byers, J.N., Hunt, J.E., McSevany, T.M., Hollinger, D.Y., Dungan, R.J., Earl, W.B. and Bourke, M.P. 1995. Performance of large open-top chambers for long-term field investigations of tree response to elevated carbon dioxide concentration. *J. Biogeogr.* 22: 365-368.

* In Japanese with English title.

** In Japanese with English title.

*** In Japanese.