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PRE-AIR-CONDITIONED TEMPERATURE GRADIENT CHAMBERS FOR RESEARCH ON TEMPERATURE STRESS IN PLANTS

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OKADA M., HAMASAKI T. and SAMESHIMA R. *Pre-air-conditioned temperature gradient chambers for research on temperature stress in plants.* BIOTRONICS **29**, 43–55, 2000. Cool summer damage is of great concern in northern Japan, the country's major rice producing region. A newly designed temperature gradient chamber (TGC) to study temperature stresses on crops is presented here. The TGC described is 3 m high, 6 m wide and 30 m long and is equipped with a pre-air-conditioning facility. Temperature at the air inlet is controllable, unlike other TGCs developed so far, where air inlet temperatures are similar to those outdoors. When pre-cooling is in operation, the maximum temperature drop at the air inlet reached 10℃ below that of outdoors on hot summer days. Apparent back flow of air has often been considered as a factor in disturbing the anticipated temperature gradient in large TGCs. In the design presented here air circulation through perforated ducts along the side walls was found to be effective in minimizing this back flow. With this effective measure linear or curvilinear temperature gradients were consistently created along the longitudinal axis and temperature differences as large as 6–8℃ were maintained between the air inlet and the outlet. By exposing rice plants to a broad range of temperature regimes, including low temperatures, both developmental rate and sterility of flowers was varied to a considerable degree.

Key words: temperature gradient chamber; air-conditioning; temperature stress; rice

INTRODUCTION

Fluctuating weather can often have a large impact on crop production. In Japan, temperatures in July and August 1993 were amongst the lowest recorded this century and caused severe low-temperature damage to crops. In particular, the yield of rice was approximately 30% of that in the average year in northern Japan, the country's major rice producing area. A new program was started at

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the Tohoku National Agricultural Experiment Station to develop experimental facilities for research on low-temperature stress in plants. A temperature gradient chambers (TGC) was designed to provide pre-cooling of incoming air in addition to a large temperature gradient, which allowed plant responses to a broad range of temperatures, including critical low temperatures, to be studied. The concept of a TGC for plant research was first proposed by Mihara (*4*) and was further developed by several workers with a special interest in global warming research (e.g. *2, 6, 8, 9*). None of these designs, however, had pre-air-conditioning facilities to control incoming air temperature, so that the temperature at the air inlet of the TGC was equal to or somewhat higher than the outside temperature. As we are interested in studying the effects of cool temperatures during summer on crops, the temperature regime created in previously designed TGCs was usually too high to study low-temperature-induced plant responses, in particular when outside was hot. The pre-air-conditioned TGC described here was designed to mimic cool summer temperature changes with field-like fluctuations. Also, as increasing atmospheric CO_2 concentration is another important concern in research on the impacts of long-term climate change, a CO_2 enrichment capacity was built into the design.

The new TGC described here was larger than any other previous TGCs in terms of size and achievable temperature gradient. As shown by previous studies, large TGCs, particularly those with a large temperature gradient, are subject to an apparent back flow effect, which can disrupt the anticipated temperature gradient. The apparent back flow is induced by buoyancy of air. Air is first heated at the floor surface and tends to ascend. It is cooled when it reaches the cover surface of the chamber. Vertical air circulation thus occurs locally and transfers heat along the longitudinal axis of the chamber. This longitudinal transfer works to mix the air from the warm end with that of the cool end. One of the most important objectives of the present study was to develop an appropriate measure to minimize this back flow effect. Here we describe in detail the design and construction of the new TGC and present control performance data as well as examples of the responses of plants growing in the chambers. Although both pre-cooling and pre-heating were available in the TGC, there was no occasion to use pre-heating in experiments conducted over the last five seasons. Hence, here we only report performance under pre-cooling mode.

CHAMBER DESIGN

Construction

The chambers were constructed with pipe hoop supports similar in design to a commercial greenhouse (Fig. 1). The dimensions were 6 m (width), 30 m (length) and 3 m (maximum height). Pipes had a 31.8 mm outer diameter and were bolted to a concrete foundation at 50 cm intervals. The wall foundations were 30 cm high above the ground level and continuously enclosed the chamber perimeter. The pipe structure was reinforced with cross beams and braces. The

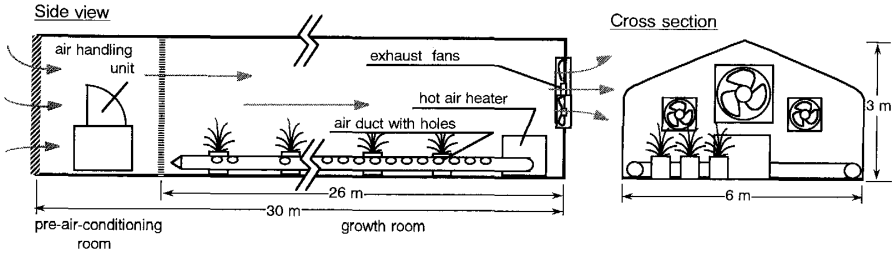

Fig. 1. Schematic drawing of the pre-air-conditioned temperature gradient chamber.

floor was paved with 20 cm thick concrete to allow easy transportation of large plant samples and to increase sensible solar heat gain.

The chamber was separated into two areas by a partition and sliding doors made from 4-layer vinylon mesh. The first 4-m span from the air inlet was used to accommodate the air-conditioning equipment (hereafter referred as the pre-chamber) and the rest of the 26-m span was used to grow plants (hereafter referred as the growth room). The pre-chamber was covered with aluminized PVC film to prevent the equipment being exposed to the sun and to reduce heat gain. The growth room was covered with 0.05 mm thick ethylene-tetrafluoro ethylene copolymer (ETFE) film (F-CLEAN, Asahi Glass Green-Tech Co. LTD, Japan). The ETFE film was selected because of its (*1*) long life and decreased dust accumulation, and hence it shows little change in light transmission with aging and (*2*) relatively high transmissivity of longwave radiation. High longwave transmissivity is required in a chamber cover material to reduce the inevitable shift in soil temperature (*6*). The transmittance of longwave radiation by the film as measured by the emissiometer method (*5*) was 0.45. This value is greater than the 0.1–0.2 for PVC or null for glass, but much smaller than the 0.7–0.8 for short-life polyethylene film.

Three chambers were constructed in total and were placed between two traditional greenhouses with the same dimensions as the chambers. They were orientated in a north-south direction. The chambers and greenhouses were spaced 5.4 m apart. This layout ensured that the three chambers received similar level of shading and experienced similar light conditions. The daily mean light transmittance observed in November and December in 1998 were 75% under overcast conditions and 65% under clear sky. These values were comparable to those obtained by Okada *et al.* (*6*) and Kobayashi *et al.* (*3*). The difference in light transmittance was insignificant among the chambers on a daily basis.

Air-conditioning system

A chiller unit with a maximum cooling capacity of 250 kW and a boiler with a maximum heating capacity of 230 kW were installed in a separate building to supply chilled or hot water to the pre-chambers. They were designed to meet the cooling and heating requirements of the three pre-chambers. Water temperature was 7–12℃ in cooling mode and 30–80℃ in heating mode. Each pre–chamber was equipped with two air–handling units, each having a maximum heat exchange rate of 55 kW in cooling mode and of 104 kW in heating mode. Water supply to the air–handling unit was regulated through a 3–way valve. Air circulation at a rate of 17,000 $m^3 h^{-1}$ induced by the two air–handling units was used both to transfer heat from the water to the air and to uniformly mix the air in the pre–chamber.

Three exhaust fans, two small and one large, were installed at the other end of the growth room, the small fans having a maximum flow rate of 3,000 $m^3 h^{-1}$ each and the large fan a maximum rate of 20,700 $m^3 h^{-1}$. Although the two small fans ran continuously, the operation of the large one was variable depending on the temperature gradient control. The rotation speed of the large fan was controlled by an inverter and varied in 4 steps from non–operation to full rotation (Null–, Low–, Middle– and High– mode; see below).

An oil–burning hot air heater with a heating capacity of 87 kW was installed near the air outlet end of the growth room. Hot air was distributed into the room through two transparent polyethylene ducts, with a duct being placed along each side of the growth room. The duct was 90 cm in diameter and had approximately thirty 85 mm diameter holes at 50–300 cm intervals at the top of the duct. The holes effectively disrupted the apparent back flow of air from the warm end (discussed below), and thus were arranged more densely at the warm end and more sparsely at the cool end. Figure 2 shows two different hole patterns used in the experiments. Because no theoretical approach was available, the hole pattern was empirically determined by trial and error by observing the temperature gradient. Though air circulation through the ducts was continuous, the end heater was activated only when solar heat gain was insufficient.

Temperature measurement and control

Five aspirated Pt100 resistance thermometers were placed equi–distantly at

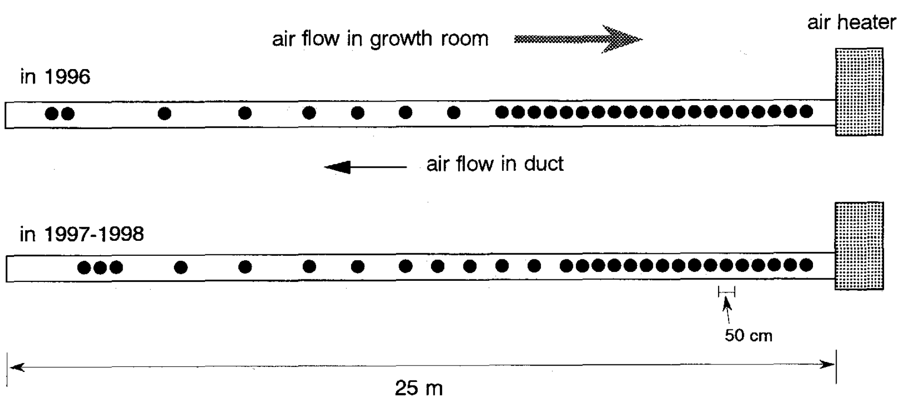

Fig. 2. Two different perforation designs of the air duct used in experiments in 1996 (top) and in 1997–1998 (bottom). Solid circles denote the locations of the air outlet holes in the duct.

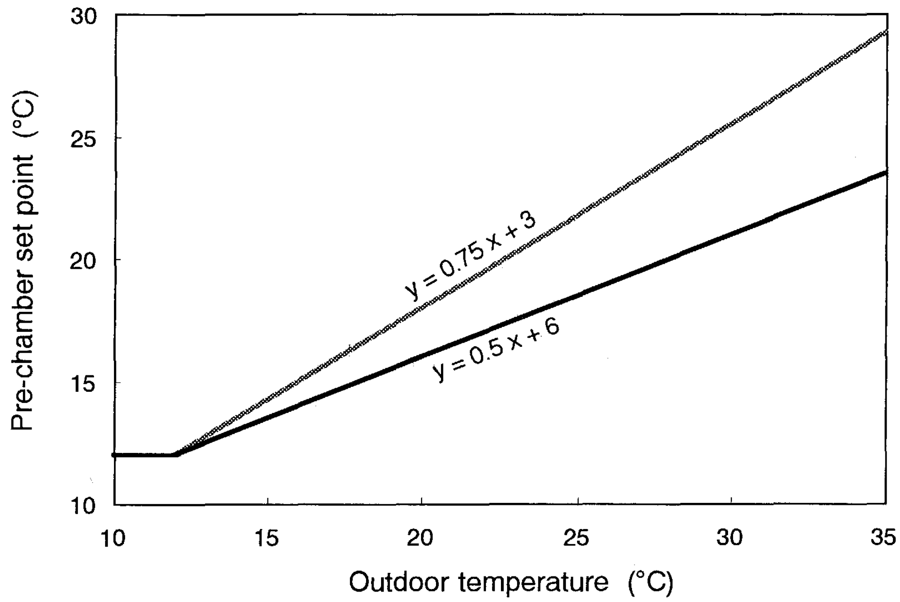

Fig. 3. Examples of pre-chamber temperature set points dependent on outdoor temperature.

the center along the length of the growth room at 1 m, 6.5 m, 12 m, 17.5 m and 23 m from the vinylon mesh partition. The height of the thermometers was variable according to plant growth, but it was usually 10–20 cm above the top of the tallest plants. Two other thermometers were placed in the pre-chamber and outdoors. Temperatures were measured every 5 seconds and their averages were recorded every 30 minutes by a data logger (GK100, ESD Co., Japan), in which a control algorithm was also programmed.

Control of both the pre-chamber temperature and the temperature gradient in the growth room was carried out at 5 second intervals. The set point of the pre-chamber temperature was given as a simple linear function of the outdoor temperature. Figure 3 shows two typical patterns for a chilling experiment, although the target temperature depended largely on the objectives of the research, plant species used and their growth stage, etc. In the case of this example the 3-way valve to supply chilled water to the air-handling units was regulated in proportion to the deviation of the pre-chamber temperature from the target.

The temperature difference between the pre-chamber and the location at 23 m from the inlet of the growth room was used as a variable in the temperature gradient control algorithm. The large fan was stepwise controlled as follows, 1) Null-mode when the difference was lower than 7℃, 2) Low-mode between 7 and 7.5℃, 3) Middle-mode between 7.5 and 8℃ and 4) High-mode when the difference was larger than 8℃. The hot air heater was activated when the temperature difference dropped below 6℃. With these set points the temperature difference between the pre-chamber and the 23 m location was 7–7.5℃. When a smaller or larger difference was required, set points were similarly determined, but decreased or increased, respectively.

CO_2 control

Commercially available polyethylene irrigation tubing (Kiriko type–R, Mitsui Kagaku Platech Co. LTD, Japan) was used to release CO_2. Five tubes were placed at the air inlet in the pre–chamber. They were different in length (32, 59, 87, 122 and 169 cm), hence differed in CO_2 emission rate at a given gas pressure (*7*). By combining a common PID algorithm and the exhaust large fan, one activated tube was selected among the five tubes. The PID components were calculated from the deviation of the CO_2 concentration from its target. An integer ranging from 1 to 4, each corresponding respectively to the Null, Low, Middle and High modes of the large fan, was added to the sum of the PID components. The value thus obtained was used to select the emission tube, with shorter tubes being used when the values were low. For instance the 32 cm tube released CO_2, when the value ranged from 0.5 to 1.5. For control purpose two infrared CO_2 analyzers (ZFP9, Fuji Electric Co., Japan) were used; one for measurement of CO_2 concentration in the ambient chamber and the other in the elevated CO_2 chamber. This concurrent measurement allowed CO_2 control in the elevated chamber to depend on the ambient CO_2 concentration with the target being 200 micromol mol^{-1} above the ambient. Since the model ZFP9 was sensitive to the change in ambient temperature and the barometric pressure, a temperature and pressure compensated CO_2 analyzer (LI6252, LiCor Inc., USA) was used to more accurately monitor the CO_2 concentration in the chambers.

RESULTS AND DISCUSSION

Temperature gradient control

As shown by Okada *et al.* (*6*), large, and particularly tall, TGCs are subject to an apparent back flow of air from the warm end, which diminishes the extent to which a temperature gradient can develop. To avoid this back flow, paddle fans (*9*) or slotted septa (*8*) have been used in previous TGC designs. Since the resultant temperature gradients in such designs were neither linear nor curvilinear, but stepwise, we tried a different approach to the problem. As discussed below, plant responses to chilling or heat stress are sometimes very sensitive to stepwise changes in temperature and it is not always possible to detect the critical temperature at which a drastic change in the response occurs.

We found the polyethylene ducts connected to the hot air heater effective in disrupting the back flow. No other measures such as baffling the triangle space below the ridge with septa or blowing the air of that space to the warm end with fans worked to minimize the back flow effect. The temperature gradient in the growth room is compared with and without ducts in Fig. 4, and it is evident that the influence of air circulation through the ducts is substantial in determining the development of consistent gradient. Without air circulation through the ducts, the gradient was unstable and neither curvilinear nor consistent. In TGCs the back flow usually develops under low airflow speed.

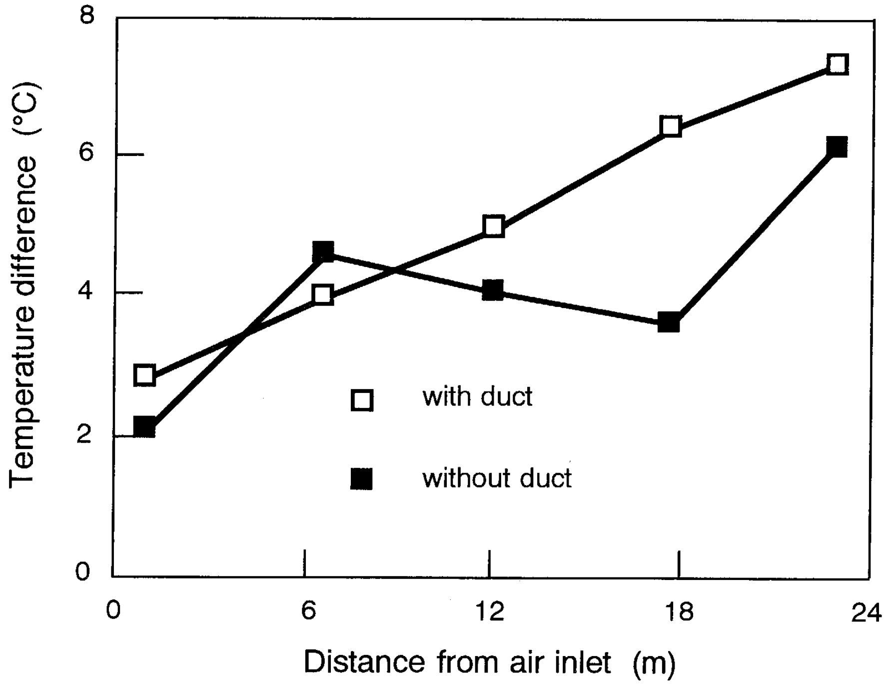

Fig. 4. Comparison of temperature gradients with and without the air circulation duct. Vertical axis is the temperature increase relative to the pre-chamber.

As the hot air heater was at the warm end, air was forced to return to the cool end though the ducts and to circulate continuously throughout the growth room. The resultant increase of airflow speed in the growth room may therefore be one of the major causes of the diminished back flow effect. Each duct had approximately 30 holes, from which air came out. As the holes were placed so as to direct air upward, cross-sectional airflow going up along the walls and roof surface was induced. Enhanced cross-sectional airflow may also have an effect in breaking the back flow. The arrangement of the holes largely influenced the resultant gradient pattern. Figure 5 compares the effects of two different hole patterns on the temperature gradient obtained; one resulted in a near linear gradient and the other in an asymptotically curvilinear gradient.

Figure 6 shows daily changes in air temperature in the TGC on hot summer days. In both cases the actual pre-chamber temperature deviated from its set point during the daytime, clearly showing insufficient cooling capacity. Cooling load depended not only on outdoor temperature but also on both outdoor humidity and solar heat gain. The smaller difference between the pre-chamber and the outdoor temperature shown for July 28th 1998 was accounted for mainly by the increased latent cooling load caused by the high outside humidity (the dew point temperature at midday was 2.1℃ higher than that for August 14th 1996). The drop in the pre-chamber temperature just before noon was caused by cloud cover leading to less solar heat gain. Data from long term operation over 5 years showed that the current air-conditioning system was able to

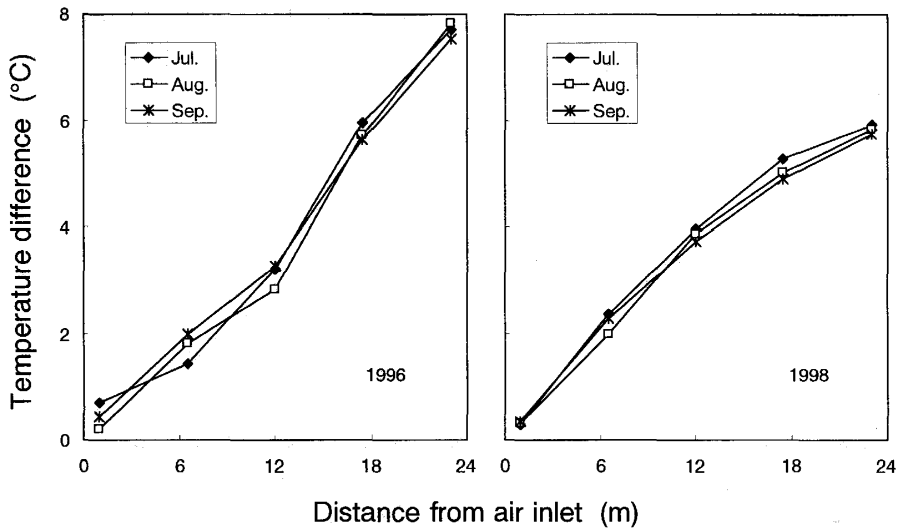

Fig. 5. Comparison of monthly mean temperature gradients inside the TGC as influenced by different perforation designs in 1996 (left) and in 1998 (right). Vertical axis is the temperature increase relative to the pre-chamber.

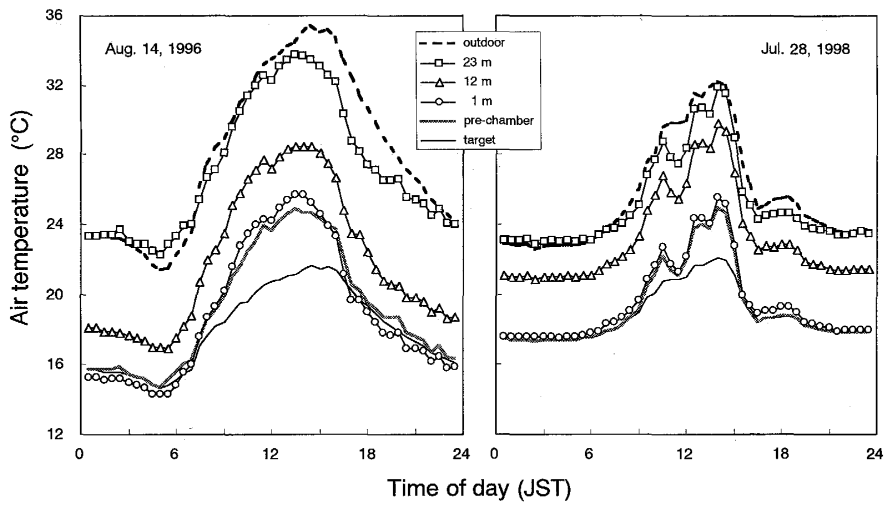

Fig. 6. Diurnal change in air temperatures in the TGC.

maintain the pre-chamber temperature at 8–10℃ below outdoors at midday under hot summer conditions.

Cross-sectional temperature profile

Both horizontal and vertical temperature profiles were measured with radiation-shielded thermocouples (0.13 mm diameter). Figure 7 shows typical horizontal profiles at different heights. The data points are the deviation from the center temperature measured at 1 m above the floor. The location where the measurement was made was at 16.5 m from the air inlet of the growth room and 80 cm downwind from rice plants grown in pots. Eight pots were placed on

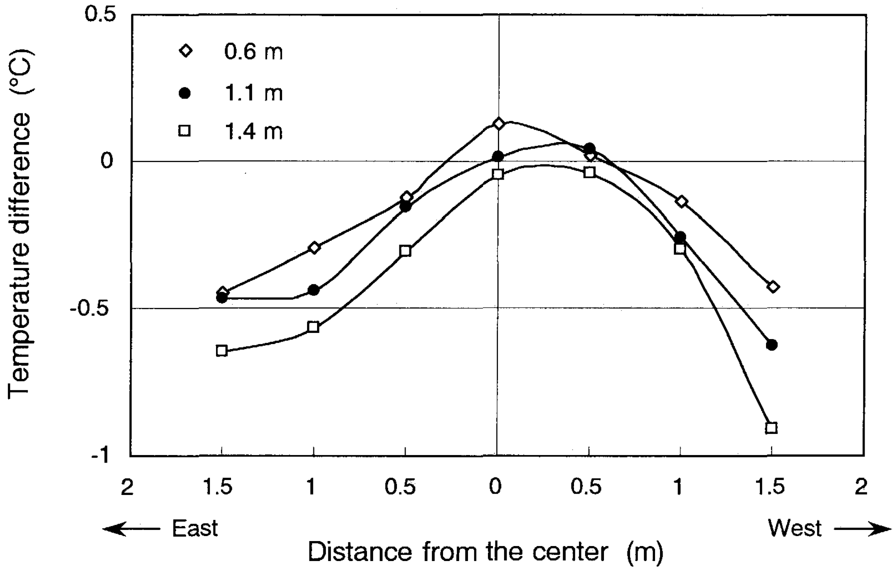

Fig. 7. Temperature profiles across horizontal axis at different heights at 16.5 m from the air inlet of the growth room. Data are shown as the deviation from the temperature measured at a height of 1 m at the center of TGC.

the horizontal axis. Total width of the plant windbreak was 3.5 m and its height was 1.2 m. In general, air temperature near the walls was lower than at the center. The deviation from the center temperature was approximately 0.5℃ at or below the plant height, while it was larger above the plant height. Such a pattern was consistent throughout the growth room. The asymmetric temperature profile across the horizontal axis was presumably caused by unbalanced distribution of air to the two separate ducts from the hot air heater blower. The development of a plenum to blow air evenly to the two ducts will be necessary to further improve the temperature distribution. In contrast to the horizontal profile, the vertical temperature difference was small except at the western edge. A warm temperature region induced by the apparent back flow was observed only near the top of the growth room above 2 m from the floor on a sunny day.

Vapor pressure

One of the most important issues of the TGC environment is the behavior of atmospheric vapor pressure. Figure 8 compares the gradients of the air temperature and the vapor pressure deficit (VPD). Because the incoming air was pre-cooled, both temperature and VPD were lower in the pre-chamber or near the air inlet of the growth room compared to outdoors. The rise in VPD was similar to that of the air temperature along the longitudinal axis of the growth room. As shown by Okada *et al.* (*6*), these two factors are closely associated with each other. In comparison to other TGC designs, a large temperature gradient was one of the distinctive features in the design presented here. The large temperature gradient, hence, resulted in the large VPD gradient.

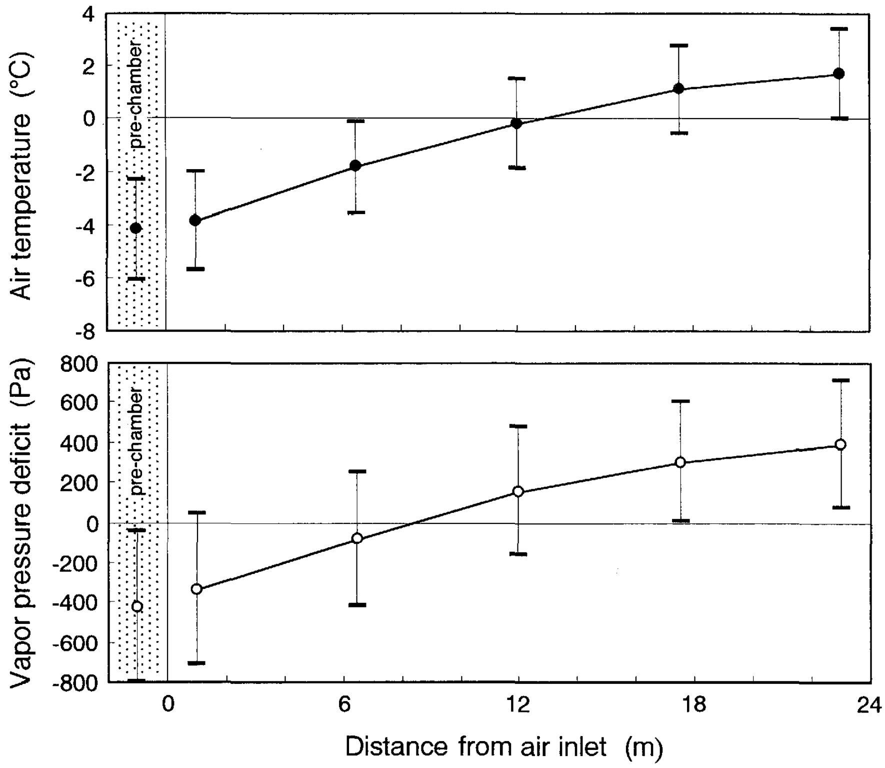

Fig. 8. Monthly mean (symbol) and standard deviation (horizontal bar) of air temperature (top) and vapor pressure deficit (bottom) along the long axis of the TGC in July, 1998. Both data are expressed as the difference of inside minus outside values.

Development of the VPD gradient might be enhanced by the dry concrete floor, but an attempt to increase atmospheric moisture content by wetting the floor had little effect on minimizing the gradient. This was because most of the time the large temperature gradient was maintained by sensible heat supply from the hot air heater. If solar heat gain of the floor surface was a major factor in creating the temperature gradient, wetting the floor surface would have reduced the VPD gradient. Unlike previous TGCs with small temperature gradients generated mainly by solar heat gain, a large VPD gradient may be inevitable when a large temperature gradient is created by sensible heat supply.

CO_2 control

Figure 9 represents the diurnal change of CO_2 concentration in the ambient and elevated CO_2 chambers. The target CO_2 concentration of the elevated chamber was 200 micromol mol^{-1} above ambient. Air samples for control were taken at 6.5 m from the air inlet. Figure 9 clearly indicates that the deviation of the CO_2 concentration from the target in the elevated chamber was small and control was adequate. The longitudinal change in CO_2 concentration was negligibly small, being less than 5 micromol mol^{-1} (data not shown). In general, CO_2 concentration decreases gradually according to plant photosynthesis across

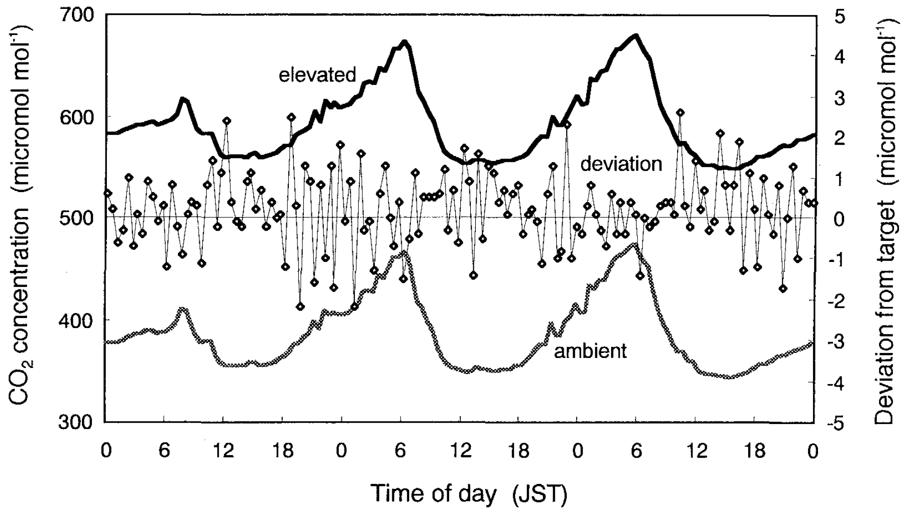

Fig. 9. Changes in CO_2 concentration in the ambient and in the elevated TGCs and deviation of CO_2 concentration in the elevated TGC from the target (ambient+200 micromol mol^{-1}). Data poiuts are 30-min averages.

the longitudinal axis of a TGC. Therefore, the drop in concentration near the exhaust end of a TGC depends largely on the number of plants accommodated in the chamber as well as their photosynthetic activity. In the present TGC approximately a half of the floor space was usable to accommodate plants and the rest was occupied by air ducts, water piping, walkways, etc. Having limited plant space compared to the floor area may have been a reason for the small longitudinal change in CO_2 concentration.

Crop responses

The temperature difference between the pre-chamber and the location at 23 m from the air inlet of the growth room was kept at 6-6.5℃ throughout rice growing season of 1997. Rice plants (*Oryza sativa* L. cv. Akitakomachi) were seeded directly in pots, which were placed at 3 m intervals along the longitudinal axis of the ambient and elevated CO_2 chambers after emergence. In May, June and September the pre-chamber was cooled according to the scenario shown by the top line in Fig. 3 and in July and August by the bottom line. Because rice spikelets are sensitive to low temperatures during the stage from panicle initiation to heading, the above scenario provided temperature low enough to induce the sterility of flowers. Rice plants exhibited large differences in both developmental stage and sterility of flowers. Heading date varied by about 2 weeks between the plants at the coolest and at the warmest end. This difference in date was nearly double of that observed in our previous TGC experiments (*6*). Percent sterility was plotted against average air temperature at the sensitive stage from 15 days to 5 days prior to heading (Fig. 10). Sterility varied from 100% to nearly zero. It is difficult to obtain such variability in a single experiment with the small temperature gradient obtained in previous TGC designs (*6*). The data set obtained here enabled us to

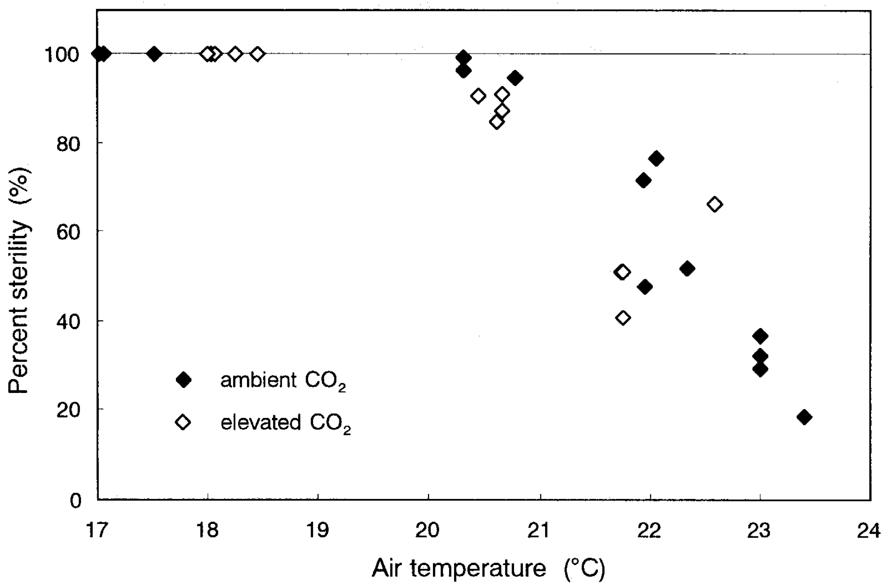

Fig. 10. Relationship between percentage of rice spikelet sterility and air temperature averaged over 15 days to 5 days before heading.

determine the critical temperature at which the sterility response changed drastically; i.e. sterility being 100% below the critical temperature and gradually decreasing above it. The critical temperature was around 20℃ in this case. The data also suggested that the influence of elevated CO_2 on sterility was insignificant.

CONCLUSIONS

The TGC described here has a pre-air-conditioning facility to control incoming air temperature across a range required for plant temperature stress research. When pre-cooling was used, the incoming air temperature was maintained low enough to conduct research on rice cool summer damage even during a hot summer season. The maximum recorded temperature drop in the pre-chamber was 10℃ below the outdoor temperature of 30℃. In addition to the usual ventilation control, supplementary heating is provided from an oil-burning hot air heater to create a large temperature gradient throughout the day and night. Temperature differences between the air inlet and the outlet of the growth room as great as 6–8℃ have been attained consistently.

Large TGCs in general are subject to apparent back flow of air from the warm end to the cool end, which disrupts the development of the temperature gradient. Although our TGC is one of the largest in the world, an air duct system to enhance both longitudinal and cross-sectional airflow has been found to be effective in minimizing the detrimental influence of the back flow. Linear or curvilinear gradients have been consistently created by use of two perforated ducts through which air is circulated from the hot air heater blower. The pattern of the gradient is adjustable by changing the arrangement of the air outlet holes in the ducts.

While CO_2 concentration has been controlled adequately for research on plant-CO_2 relations, vapor pressure is still uncontrolled, as indicated in the previous studies. Shifts in the air-soil or air-plant temperature relations have been observed (*1*).

Data from experiments to investigate cool temperature induced sterility in rice indicated the effectiveness of the TGC described here to elucidate temperature stress responses of plants.

ACKNOWLEDGEMENTS

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