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TEMPERATURE GRADIENT CHAMBERS FOR RESEARCH ON GLOBAL ENVIRONMENT CHANGE. I. THERMAL ENVIRONMENT IN A LARGE CHAMBER

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OKADA M. HAMASAKI T. and HAYASHI T. *Temperature gradient chambers for research on global environment change. I. Thermal environment in a large chamber.* BIOTRONICS **24,** 85–97, 1995. Simple and low-cost temperature gradient chambers (TGC) have been developed to study the effects of temperature on field crops. Providing a continuous one-way air flow along the long axis of the TGC, the air temperature rises gradually with distance from the inlet by sensible heat gain form solar radiation or supplementary heating cables. The chambers described here are 2 m high, 3.6 m wide and 18 m long greenhouses with exhaust fans installed at one end and air inlets at the other end. The monthly mean temperature differences between the air inlet and the outlet resulted in 2 to 3°C temperature increase during summer-crop seasons. Reducing the ventilation rate led to temperature increase, but did not increase the temperature gradient in the chamber. It became clear that the air flow velocity must be large enough to break an apparent backflow in the TGC induced by convection. Alteration of the air-soil temperature relationship was observed in the chamber in comparison to field conditions. This alteration appears to be inevitable in the TGC, since both longwave rediative heat loss and convective heat exchange are small in enclosures like a TGC.

Key Words: temperature gradient chamber; global environment change; rice.

INTRODUCTION

Projected changes in the global environment have resulted in renewed interests in new techniques to study plant growth and development under differing environmental conditions. The important environmental factors that need to be studied include temperature and atmospheric CO_2 concentration.

Current methodologies do not allow the potential interactions of elevated atmospheric CO_2 concentration and increased temperatures interaction to be studied readily. The cost and limited amount of plant material produced using existing methodologies are also serious constraints on introducing other factors such as water and nutrient availability into global environment change research. Fortunately, an emerging methodology offers the possibility of studying in a single experimental array several of the interactive factors that can influence plant responses to global environment change. This methodology uses large, horizontal chambers constructed over field plots. As air is drawn through the chambers it is heated either by solar radiation or by supplemental heaters. Consequently, plants can be exposed to a range of increased temperatures as a result of the gradient of increasing temperature that is established in the chamber – hence the name Temperature Gradient Chamber(s) (TGC).

The interaction of temperature increase with elevated CO_2 is readily studied by constructing several TGC and maintaining each at a different CO_2 concentrations. Because the airflow in a TGC is relatively low to maintain the temperature gradient, the requirements for supplemental CO_2 are also minimized. As a result, several TGC provide plant growth environments for studying responses to elevated CO_2 concentrations under an array of increased temperatures. The large size of the TGC may also allow other environmental variables to be introduced into the research. Generally, TGC provide relatively large amounts of plant material for study and sampling.

The concept of a TGC for plant research is not new. Mihara (*5*) proposed a temperature response curve technique to separate the effects of temperature on plants from the effects of other environmental factors. His TGC was a 50-cm high and 10-m long plastic tube greenhouse with an air inlet at one end and an exhaust fan at the other end. When the inside air was ventilated by the fan, an air temperature gradient was created along the long axis of the greenhouse in the daytime. The magnitude of the gradient depended on solar heat gain. In contrast to a usual air-conditioned growth chamber, the chamber of Mihara tracked a natural diurnal change of temperature and produced increased temperatures for study of crop responses.

Existing concepts for greenhouse ventilation design can be used to estimate quantitatively the temperature gradient that might develop in a chamber subjected to solar heating. The following equation is derived from greenhouse design theory (*7*) to assess the temperature increase.

$$\Delta T = H/(C_p \rho \ V + 0.5\ \alpha h_t) \qquad (1)$$

Where ΔT is air temperature difference between the air outlet and the inlet of the chamber (℃), H is sensible heat gain (W m^{-2}), C_p is specific heat of air (= 1004 J kg^{-1} ℃$^{-1}$), ρ is density of air (=1.2 kg m^{-3}), V is ventilation rate (m^3 m^{-2} s^{-1}), α is ratio of cover area (roof + walls) to floor area, h_t is heat transmission coefficient through cover (W m^{-2} ℃$^{-1}$). The factor 0.5 is given when the inside mean air temperature is assumed to be the average of the temperatures at the air inlet and at the outlet in the TGC. Equation (1) is expressed on a unit floor area basis. The solar radiation absorbed in the chamber is distributed to sensible heat convection, evapotranspiration and soil heat transfer. The values of these variables depend lagely on the outside weather conditions as well as on the inside crop and soil conditions. In a conventional greenhouse the sensible heat gain (H) ranges from 20 to 35% of the external solar radiation (*7*). For plastic covered greenhouses 6 W m^{-2} ℃$^{-1}$ is a good approximation for the heat transmission coefficient (*6*).

Equation (1) indicates the importance of ventilation rate (*V*) on the temperature gradient in the greenhouse. With appropriate ventilation controls it is possible to establish a rather stable temperature gradient along the chamber. The TGC reported in this series of papers have been constructed in the field and are of sufficient size to allow large plant populations to be studied. They have proven to be relatively inexpensive to construct and operate. The relatively low airflow rates through the TGC also make them especially economical in elevated CO_2 studies.

The objectives of the work described in this first paper in a series of two papers were two-fold. (1) Investigate the possibility of developing a large TGC for field ues. For field crops such as rice, soybean and sorghum, the TGC must be sufficiently tall to allow normal plant development. (2) Fully document and characterize the temperature environment inside the large TGC. In large chambers, airflow patterns and localized temperatures may disrupt the anticipated temperature gradient. The second paper by Sinclair *et al.* (*8*) reports refinements on the design presented here which make TGC especially useful in establishing temperature plots within the TGC. This paper also presents a simple design for regulating CO_2 concentrations in TGC.

CHAMBER DESIGN

Construction

The TGC were constructed using commercial-type greenhouses with steel pipe hoop supports (Fig. 1). The dimensions of the chamber were 3.6 m in width, 2 m in height and 18 m in length. Pipes were 19 mm in outer diameter. This structure was constructed by burying the ends of the hoop in the ground at 50 cm intervals. The greenhouse was covered with 0.1 mm thick UV-transparent polyvinyl chloride film (Table 1).

The TGC were laid in north-south orientation to obtain fairly uniform spatial distribution of direct solar beam in summer (*3*) and to minimize the influence of shading of neighboring chambers in winter (*4*). In total, 4 TGC were constructed, 4 m apart from each other. The daily mean light transmittance observed under clear sky conditions ranged from 77% (July 8) and 69% (November 8), decreased as the altitude of the sun decreased. The light transmittance under overcast conditions exhibited small diurnal and seasonal

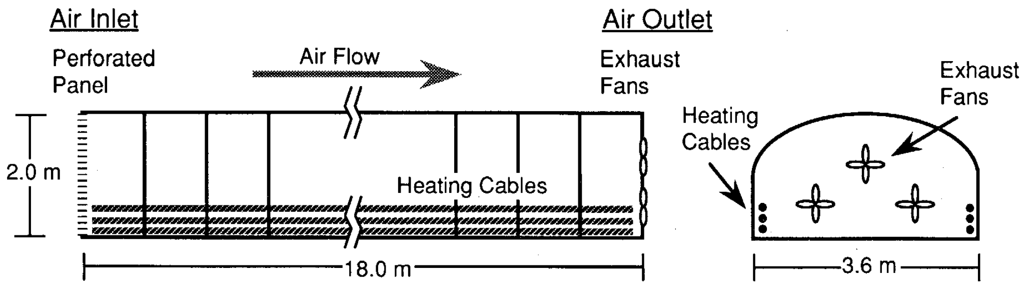

Fig. 1. Schematic drawing of temperature gradient chamber.

Table 1. Suppliers of materials and equipment

Material/equipment	Make/model	Supplier (Japan)
Chamber framework	19 mm Galvanized steel pipes & joint parts	Taiyo Kogyo Co., Yahaba, Iwate (any greenhouse suppliers)
PVC film	Nobi-ace 25 m×7.5 m×0.1 mm	Mitsubishi Kasei Vinyl Co., Chiyoda, Tokyo
Air fans	PF30-BSC	Mitsubishi Electric Co., Chiyoda, Tokyo
Heating cables	Engei Cable 100 V, 500 W, 20 m	Sakata-no-Tane, Minami, Yokohama
Data logger	Green Kit 100	ESD Co., Bunkyo, Tokyo
Personal computer	Dynabook J3100 SS002	Toshiba Co., Minato, Tokyo

variations, but averaged 72±2%. The results were comparable to those by Kobayashi *et al.* (*2*), who reported 75% for the mean light transmittance during the summer in a similar type of chamber.

Perforated panels were used as air inlets to regulate incoming air flow. Each hole was 10.5 mm in diameter and evenly distributed in 3-cm grid on the panel. Holes were added in the center of the grid on the upper half of the panel to give increased air flow through the upper section. Three exhaust fans were installed at the other end. The ventilation capacity of each fan was 28 $m^3 min^{-1}$. The mean air flow velocity in the transverse section was 26, 17 and 9 cm s^{-1} in 3-fan, 2-fan and 1-fan operating modes, respectively. Provided $H=200$ W m^{-2} and $\alpha=2$, the temperature difference between the outlet and the inlet calculated from Eqn. (1) is 6℃ when three fans are operating.

Temperature measurement and control

Air temperature was measured at 1 m, 6 m, 11 m and 16 m from the air inlet by resistance thermometers. The temperature difference between two locations (16 m-1 m) was used for the temperature control variable. Two fans worked continuously and the third fan was swiched on when the temperature difference exceeded 3℃; namely a gradient of 0.2℃/m. Electric heating cables (3kW) were placed close to the side walls and were activated when the temperature difference was smaller than 2℃; a gradient of 0.13℃/m. According to Eqn. (1), 3kW sensible heat gain alone can raise the air temperature by 2℃ under the 2-fan operating mode. This simple algorithm was implemented by an intelligent data logger which controlled 4 TGC. Temperatures were measured every 20 seconds and their averages were recorded every 30 minutes by the logger. This system has continuously operated for 4 years.

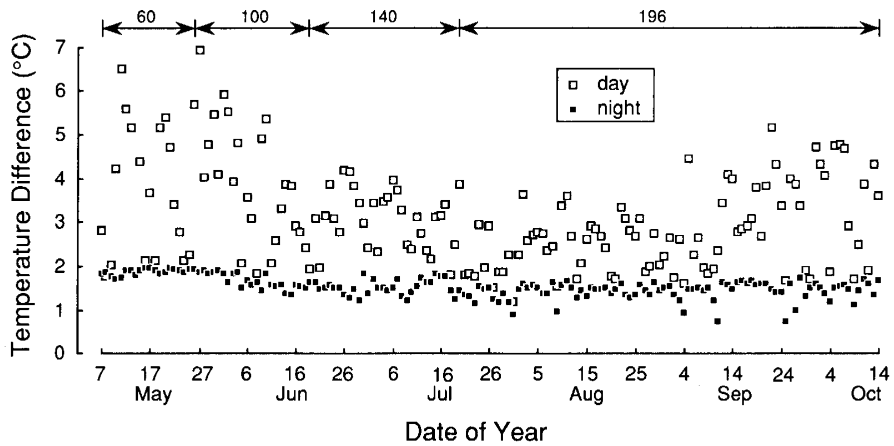

Fig. 2. Seasonal changes of temperature differences between two locations at 16 m and 1 m from the air inlet; day: mean over a 4-h period (1000–1400 h), night: mean over a 6-h period (2100–300 h). Figures indicated above arrows denote the number of pots placed in TGC.

Cost of the system

The initial costs of the components required to construct one chamber were approximately US$400 for the structural materials including pipes, joint parts and film, US$900 for three sets of the fan and the shutter and US$600 for six 500 W heating cables (totally 3 kW). It is necessary to replace the film every year, as light transmission decreases annually due to dust accumulation. This costs approximately US$200. The cost of the system engaged in the temperature measurement and control of 4 TGC was approximately US$9,500 including 16 thermometers, 1 data logger and 1 personal computer.

THERMAL ENVIRONMENT IN TGC

Temperature gradient

Figure 2 shows a seasonal change of the air temperature difference between the locations at 16 m and at 1 m from the air inlet during summer crop seasons. The daytime averages were for a 4-hour period (1000–1400h), when the temperature difference was usually the lagest, and the night for a 6-hour period (2100–300h), when the chamber received no solar heat. The day temperature gradient depended to a considerable extent on solar radiation, but showed a gradual decrease through August. This decrease was presumably caused by increasing evapotranspiration in the chamber. The figures indicated above the arrows in Fig. 2 denote the number of pots of rice plants placed in the chamber, each pot having the soil surface area of 314 cm^2. Since the soil surface was usually covered with water, water surface occupied 9.5% of the floor surface when there were 196 pots. The LAI reached a maximun 0.6 in the middle of August. The increase of the evapotranspiration with LAI resulted in a decease in sensible heat gain. The sensible heat gain on a sunny day was estimated

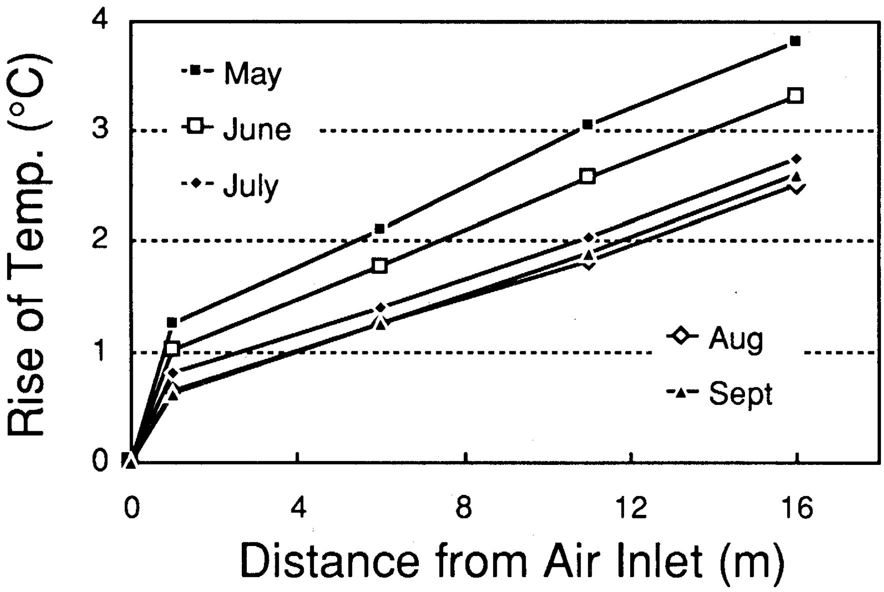

Fig. 3. Monthly mean air temperature gradient inside the chamber. Vertical axis is expressed as a temperature difference between inside and outside air.

from Eqn. (1) to be 200–220 W/m^2 at its maximun, when the temperature difference reached 6–7℃, and was reduced to 100–130W/m^2 by increasing evapotranspiration. The seasonal mean temperature difference during the night was 1.6℃ between 16-m and 1-m locations, corresponding to 80% of that predicted by Eqn. (1). This indicates that 80% of the heat output of the electric cables was available for the sensible heat gain.

Figure 3 illustrates the monthly mean temperature difference between the inside and outside of the chamber. A linear increase of temperature was observed along the chamber except in the zone close to the air inlet. The temperature gradient in our system was 2 to 3℃ during summer crop seasons.

The variation of the temperature across the width of the chamber showed no consistent pattern during the daytime. This may have resulted from increased convection with the large heat input. At night, especially when the air outside was still, the temperatures right above the heating cables became 0.2–0.3℃ higher than those at the other locations. For this reason the plants were placed at least 30 cm away from the cables.

Apparent backflow problem

As shown in Fig. 3, a sudden increase of temperature was observed near the air inlet. This increase was more noticeable when the ventilation rate was small (Fig. 4). The temperature at 16 m in the 1-fan mode was triple that in the 3-fan mode. This is a reasonable consequence of the different ventilation rates. However, the gradients were not different between the two modes. Figure 5 compares vertical profiles of air flow velocity and temperature under sunny and cloudy conditions in the 3-fan mode. Under a small temperature gradient the

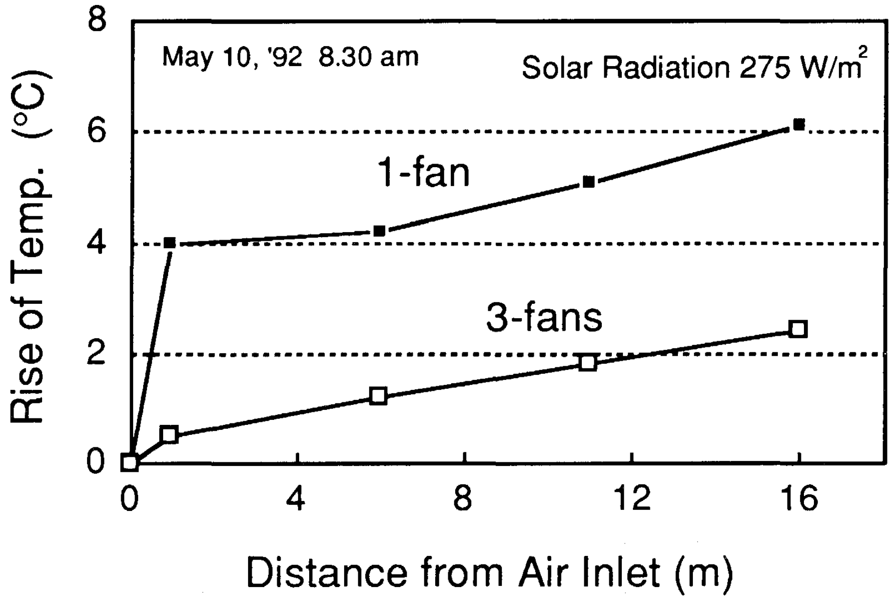

Fig. 4. Comparison of temperature gradients between 1–fan and 3–fan modes.

profiles were fairly uniform, while under a large gradient the velocity decreased and the temperature increased with height above the ground level. This suggests that the incoming cooler air tends to flow near the ground surface, but once it is heated at the surface, it tends to ascend by buoyancy. When the velocity of main air stream is small, warmer upper air layer flows backward and air mixing becomes large along the length of the TGC.

In our first version of the control program the 1–fan mode was employed for the minimum step of the ventilation to increase the temperature gradient. This program worked successfully in the 1–fan mode with electric heat during the night, resulting in the temperature rise of 2.5–3℃ along the chamber. However, it often failed to activate the second fan after sunrise, because the solar heat input increased the temperature through the whole chamber but not the gradient under the 1–fan mode. The present version of the program, therefore, employed the 2–fan mode for the minimum step, where such failure rarely occurred. The larger minimum ventilation rate may be required in a taller TGC, since the convection and its resultant backflow may become larger as the height of the chamber increases.

Air–soil temperature relationship

Many aspects of microclimate in chambers have been discussed in comparison to field coditions (*e. g., 1*). Although the alteration of air temperature was intentional in the TGC, the behavior of soil temperature was one of the important unknown factors. The daily mean soil temperature measured at a depth of 5 cm are plotted against the daily mean air temperature in Fig. 6. Since the data were collected from the second day of two consecutive clear days, the

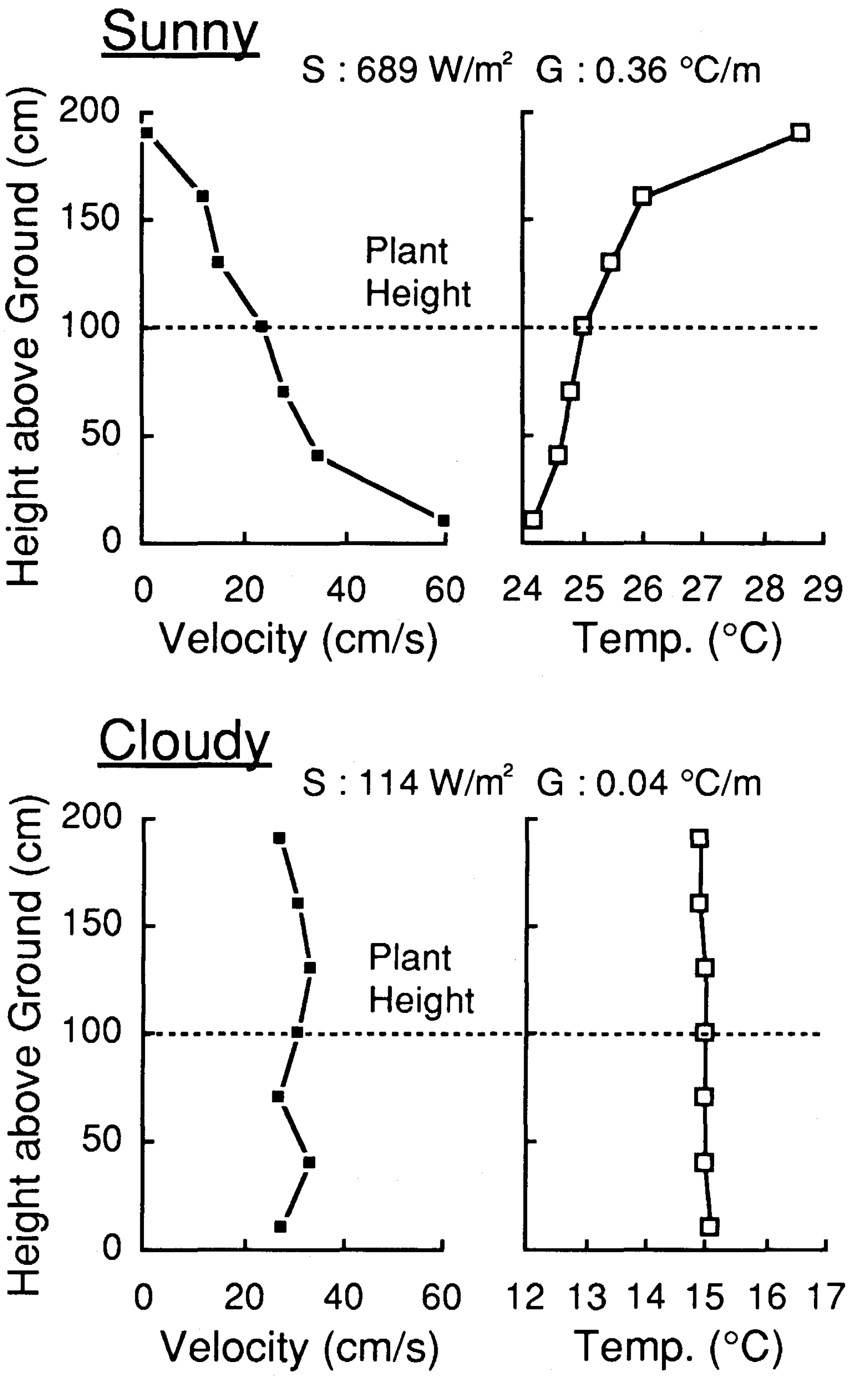

Fig. 5. Profiles of air flow velocity and air temperature.
S: outside solar radiation, G: temperature gradient

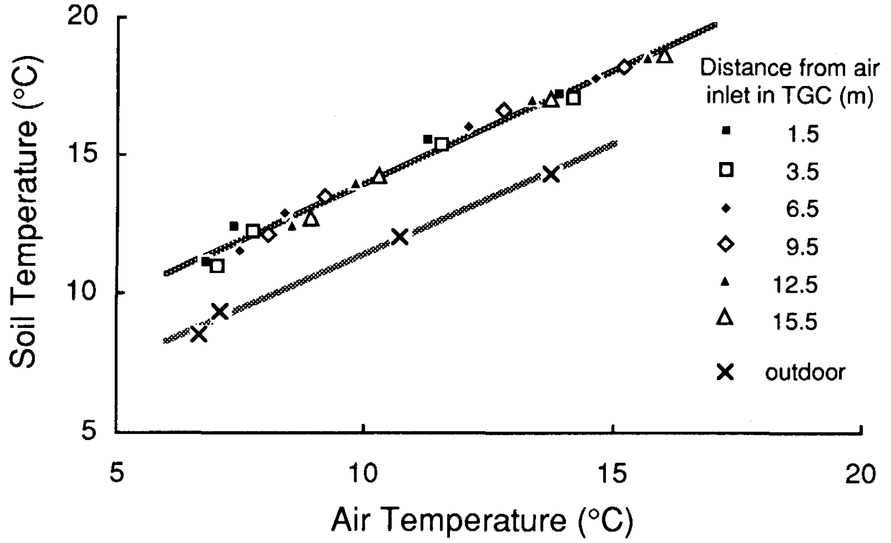

Fig. 6. Relationship between soil and air temperatures in TGC and outdoors.

influence of a phase delay on soil temperature was small. The soil was irrigated similar to a paddy field and no crop was planted. The difference between the soil and the air temperatures was approximately 2℃ larger in the TGC than outdoors. As suggested by Unsworth (*9*), the shift of the soil temperature may be caused by both small longwave radiative dissipation under plastic cover and small convective heat exchange due to low air flow speed. Accordingly the increase of soil temperature appears to be inevitable in the TGC.

Vapor pressure deficits

One of the largest questions arising on the TGC environment is the behavior of atmospheric vapor pressure. Figure 7 compares the gradients of the temperature and the vapor pressure deficit (VPD) when the floor of the chamber was sufficiently irrigated before the measurement (Wet) and when it had not been irrigated for 2 days before the measurement (Dry). Although both temperature and VPD increased from the air inlet to the outlet, a parallel relationship between the two factors was observed; *i. e.* the small temperature gradient associated with the small VPD gradient. Therefore, if the rise of VPD must be kept small, the maintenance of a large temperature gradient in the TGC is difficult without large supplementary sensible heat input.

CROP RESPONSES

Phase development

Figure 8 correlates the developmental rate of rice to the mean air temperature. The developmental rate is defined as an inverse of the number of days from emergence to heading. The symbols for each cultivar are separated into 5 groups, each corresponding to different times of planting. The

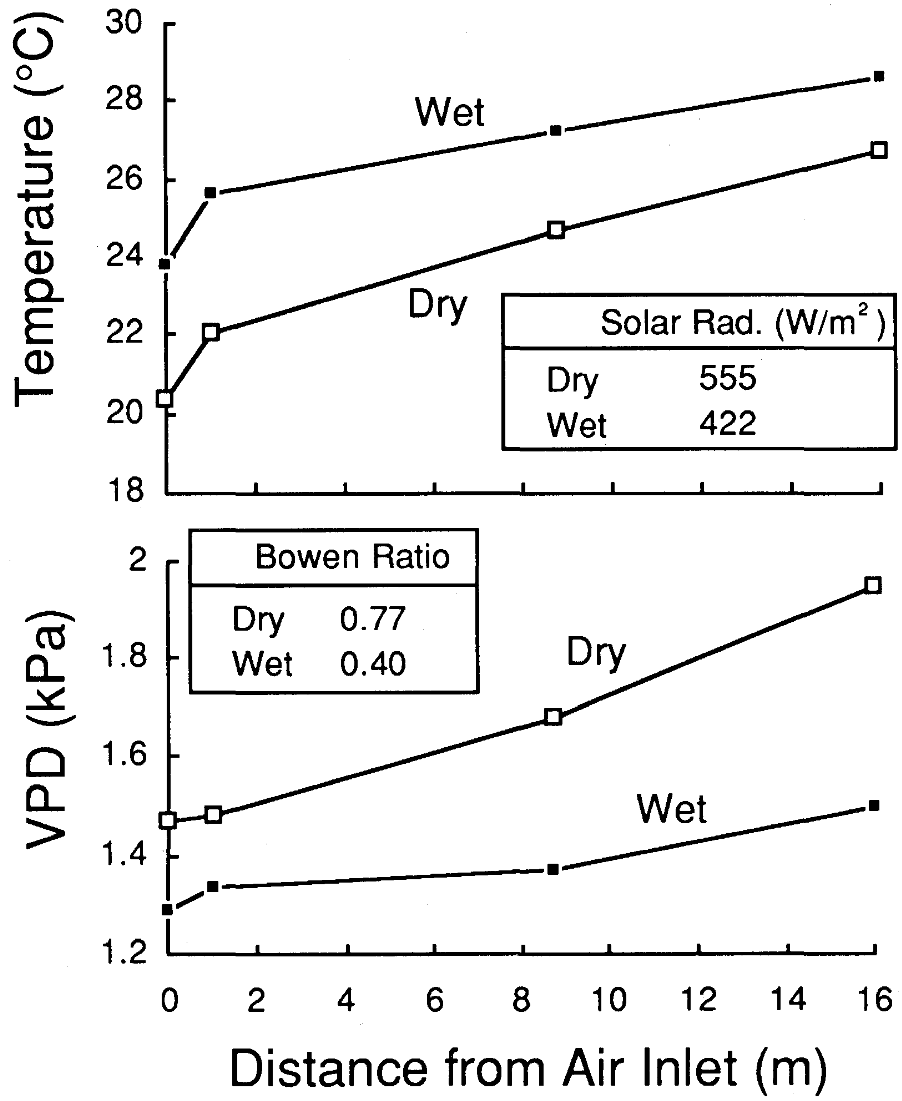

Fig. 7. Gradients of temperature and vapor pressure deficits under dry and wet floor conditions.

dependence of the developmental rate on temperature was observed within the same group. For the low photoperiod-sensitive cultivar *Akihikari*, a smooth curve can be drawn through the groups. For the high photoperiod-sensitive cultibar *Koshihikari*, each group was apparently affected by the difference in time of planting; namely in a photoperiod to which the plants were exposed. However, the linear relationship between the developmental rate and the temperature was observed within each group. The technique to grow plants in different seasons has often been used to observe the dependence of crop responses on temperature under field conditions. This technique alone may work successfully for low photoperiod-sensitive crops, but not for high sensitive ones. Incorporating TGC experiments into the technique is a useful approach to separate the effects of temperature from those of a photoperiod.

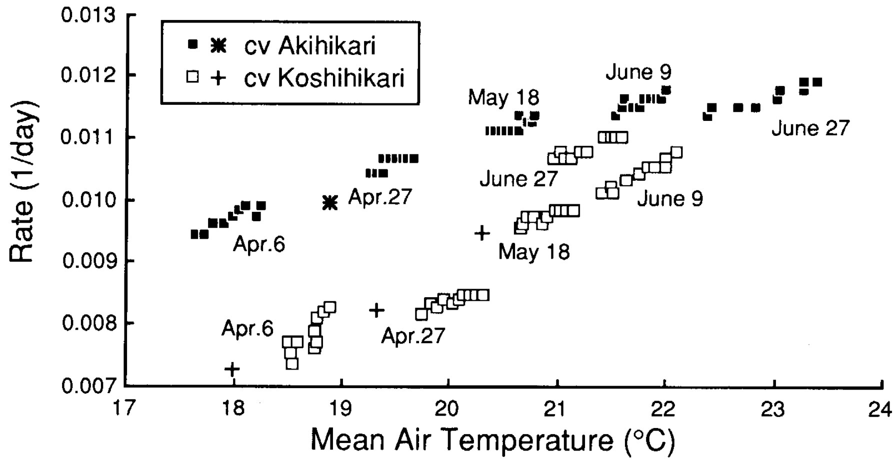

Fig. 8. Dependence of developmental rate (an inverse of the number of days from emergence to heading) of 2 rice cultivars on mean air temperature. Letters close to symbols denote the date of emergence.
Rectangles: TGC, Crosses: open field.

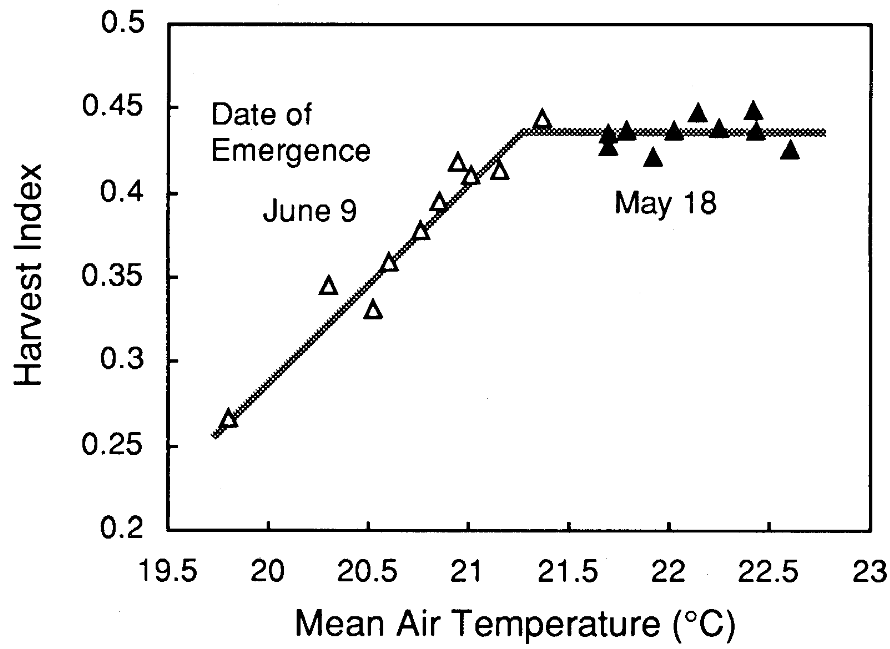

Fig. 9. Dependence of harvest index on mean air temperature from 20 days before heading to 10 days after heading.

Cool summer temperature damage

To obtain the rice growth data differing in the floral fertility, the plants were exposed to the temperature gradient during cool seasons. Figure 9 relates the harvest index of rice plants to the mean air temperature during the stage sensitive to cool temperature. Two data sets plotted in the figure are obtained from different times of planting. The earlier crops were less exposed to a critical cool temperature, while the later ones were to a certain degree dependent on the location in the TGC. A linear decline of the harvest index was observed below 21℃. These results, which are helpful to model the effects of cool temperature on floral damage and the resultant dry matter production, are difficult to obtain from the usual field experiments.

CONCLUSIONS

The TGC described here are inexpensive and easy to construct with the construction materials such as pipe supports and plastic film which are widely used in commercial greenhouses in Japan. With exhaust fans, supplementary heating cables and the controller, the TGC system has been found to create the expected range of the temperature gradients on a monthly average basis. The minimum air flow rate to avoid the detrimental backflow caused by convection has been found to be approximately 20 cm s^{-1} in the case of our 2-m high TGC. The air-soil temperature relationship is altered in comparison to field conditions. This suggests that the plant-air temperature relationship may also be altered. Control of the inside vapor pressure deficits is difficult as long as the temperature gradient is a primary variable to be controlled. The examples of the rice growth data have indicated the effectiveness of the TGC to observe crop responses necessary for modeling.

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