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High Performance of Temperature Gradient Chamber Newly Built for Studying Global Warming Effect on a Plant Population

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ABSTRACT: To study the effect of global warming on the growth of plants and plant populations throughout their life cycle under a field-like condition, we constructed a Temperature Gradient Chamber (TGC) in Tsukuba, Japan. The chamber had slender shape: 30 m long, 3 m wide, and 2.5 m high. That satisfactory performance was confirmed by a test throughout all seasons in 1998: the projected global warming condition in the near future was simulated. That is, independent of a great daily or seasonal change in ambient meteorological conditions, air temperatures at the air outlet were warmed 5℃ higher than those at the ambient (the annual mean was 14.3℃) with precision of ±0.2℃ (the annual means were 19.2℃) with a rising rate of approximately 1℃ every 5 m. This chamber will enable us to study the effects of global warming on growth of plants and plant populations because their abilities to control air temperature are excellent. TGC is expected that it would be utilized for studying the effect of global warming on plant growth under natural weather conditions.

Key Words: Field-like conditions, Global warming, Plant population, Solar radiation, Temperature Gradient Chamber

INTRODUCTION

The atmospheric CO_2 concentration has recently increased approximately from the pre-industrial level of 280 up to 360 ppm (Schimel *et al.* 1996). This increase has been primarily driven by the rapidly growing human population, and its high consumption of fossil fuel, cement manufacturing, and deforestation (Watson *et al.* 1990, Vitousek 1994). In spite of the effort for reducing emissions of greenhouse gases, CO_2 is still increasing at a high rate of 1 to 2 ppm per year (Gribbin and Gribbin 1996); the atmospheric concentration is predicted to reach twice the pre-industrial level (280 ppm) in the next century (IPCC scenarios IS92a and IS92e 1996). Climate models, taking into account greenhouse gases and aerosols, calculated that the mean surface temperature could rise by about 1 to 3.5℃ by 2100, depending on locations (IPCC 1996).

Increasing CO_2 and simultaneous temperature rise should influence present vegetation in the world because they are important factors for plant growth, development and function. Currently, even though effects of elevated CO_2 on plant growth were studied well, very few data showed the potential effects of increased temperature under the natural weather rhythm on plant species. In this context, it is essential to conduct experiments on the responses of wild species under more realistically simulated global warming conditions. Such experiments, however, pose many difficulties because of requirements for high-level regulation techniques and great expenses to maintain proper experimental conditions and to construct facilities.

Ultimately, we search for a more realistically designed facility for the global warming experiment under the field-like condition because it is needed to determine true effects of global warming on current natural ecosystems (Morison and Lawlor 1999). Therefore, the best facility to study the effects of global warming should include the higher CO_2 and warmed condition simultaneously because they are essential environmental factors for all plants.

Temperature Gradient Chamber (TGC, Horie *et al.* 1995, Okada *et al.* 1995, Sinclair *et al.* 1995, Batts *et al.* 1998) based on the idea developed by Mihara (1971) is a facility available for studying the effect of temperature increase from present to predicted future on plant growth. Currently, temperature gradient in the TGC has very low precision because ventilation

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*Author for correspondence (present address): Terrestrial Environment Research Center, University of Tsukuba, Tsukuba, Ibaraki 305-8572, Japan (tel+81-298-53-2531; fax+81-298-53-2530; email jaeseok@erc2.suiri.tsukuba.ac.jp) rate is operated by digital-control method. This method has only some ranks for controlling ventilation rate.

In this study, we have attempted to improve the precision of temperature gradient chamber related to the change of air temperature due to extremely fluctuating solar radiation in natural condition with a simple technique and low cost in operation.

MATERIALS AND METHODS

Chamber design

The chamber was built at the Environmental Research Center of the University of Tsukuba (36° 1′ N, 140° 1′ E), Japan in 1996~1997. Long sides of the chamber were along the azimuth direction of 35°. It was 2.5 m high, 3 m wide and 30 m long, and was constructed using a commercial free-standing greenhouse tunnel (Fig. 1). The framework consisted of a series of semi-circular support pipes (ϕ22.1 mm coated with zinc. Taiyou Kogyou, Tokyo, Japan; cf. Table 1) connected by pipe joints. Both ends of the pipes (0.3 m long) were anchored in the soil. A ridge pipe running perpendicular to support pipes anchored the pipes together at 0.5 m intervals. The frameworks were covered with 0.15 mm thick UV-transparent polyvinyl films (Super Solar Muteki, Mitsubishi, Tokyo, Japan; Table 1) that have a transparency of 65~87% at wavelengths of 250~700 nm. The films were fixed on the frameworks with metal fittings, and their ends were buried in the soil to prevent ambient air from entering the chamber along their lengths. To recover the reduction of transmissivity due to deposition of dusts we cleaned the outer surface of the film with a sponge brush once every month.

The wall of the cool end of the chamber was covered with porous polypropylene screen (8×8 clear strands per cm). By adjusting the number of sheets, we were able to control the appropriate amount of air introduced into the chamber; that is, the cool end wall was covered with three-, two-, or one-screen sheets from the soil surface to 0.75 m, from 0.75 m to 1.7 m, and from 1.7 m to the top, respectively. This fine adjustment succeeded in preventing the reversal phenomenon often found in the former TGC experiments in which the air temperatures near the air outlet were lower than those near the air inlet; this reversal was caused by counter-flow of warmed air (e.g. Okada *et al.* 1995).

Creation of a temperature gradient under high solar radiation during the daytime

The air in the chamber was naturally heated by incident solar radiation; the temperature gradient was created by flowing air from the air inlet to the outlet. In order to achieve the target temperature difference between the air inlet and 25 m, the ventilation rate was controlled according to the fluctuation of air temperature caused by change of the incident solar radiation.

As shown in Fig. 1, four ventilators (FK-VP404203 and 60607, Fulta Co. Japan; cf. Table 1) installed on the wall of the warm end were operated in proportion to the frequency ranging from 10 to 50 Hz of the inverter under voltage of 200 AC. As a rule, two of the ventilators (total of maximum ventilation capacity of 285 m^3 /min) were mainly operated to keep optimum ventilation rate in the chamber, and the other two ventilators (total of maximum ventilation capacity of 200 m^3/min for two) were additionally operated when incident solar radiation exceeded about 800 W/m^2. The ventilation rates were adjusted every 10 seconds through digital signals from a personal computer by applying a proportional integral-differential (PID) control algorithm (Hendrey *et al.* 1993) based on the temperature measured (Copper-Constantan wires, 0.3 mm, Ninomiya Densen Co. Tokyo, Japan; cf. Table 1) 10 cm above the canopy. When the temperature difference was higher than 5℃ (the set

Table 1. Suppliers of materials and equipments

Materials/equipment	Makers/models	Suppliers (Japan)
Chamber frameworks steel pipe & joint parts	22.1 mm Galvanized	Taiyo Kogyo Co., Tokyo
PVC films	Super solar muteki	Mitsubishi Chemical Co., Tokyo
Ventilators	FKVP404203, 60607	Fulta Electric Co., Tokyo
Copper-Constantan wires	0.3 mm	Ninomiya Densen In. Co., Tokyo
Inverters	A024, A044	Mitsubishi Electric Co., Tokyo
Pyranometers	MS-42	EKO Co., Tokyo
Oil heaters	EH-50N	Ennez Co., Gunma, Tokyo
Blowers	BLW100-401	Fulta Electric Co., Tokyo
Data logger	Green Kit 100	ESD Co., Tokyo
Software for data logger	DL300	ESD Co., Tokyo
Personal computer for Windows 95/98		NEC, Tokyo

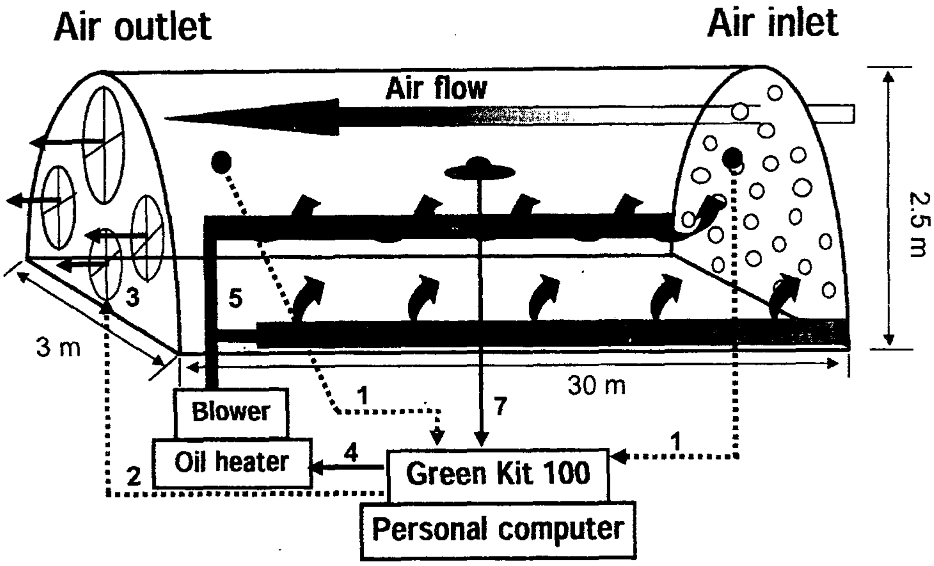

Fig. 1. Schematic drawing of temperature control system in the chamber. The different arrows indicate different pathways for controlling ventilator and oil heater in high (dotted) and low (solid) solar radiation, respectively. The numbers indicate; 1, thermocouple to measure air temperature; 2, output to control ventilator; 3, ventilator; 4, output to control heater; 5, duct to supply warmed air; 6, pipe for supplying warmed air: 7, pyranometer.

value), the personal computer sent a new percentage data between 0 to 100%, calculated on the basis of the difference between the actual temperature difference and 5℃.

Creation of a temperature gradient under low or no incident solar radiation

To maintain the temperature gradient for all time, we set an oil heater (EH-50N. Ennetsu. Gunma, Japan; cf. Table 1) which was fixed near each of the chamber. When incident solar radiation measured by two pyranometers (MS-42, EKO., Tokyo, Japan; Table 1) decreased below a set value, the oil heater was automatically turned on. The warmed air was supplied through holes of one PVC pipes set at each side in the chamber (cf. Fig. 1). The holes on the PVC pipe were opened with 0.5 cm in diameter at about 50 cm intervals. The oil heater was turned on when incident solar radiation decreased below a set value of 180 to 220 W/m^2 (e.g. it was higher in vegetative stage than in reproductive stage) because the rate of temperature rise depended on such conditions as leaf area index of plant populations in the chamber.

Ventilation rate was automatically increased if the temperature difference between the air inlet and the outlet exceeded the set point of 5℃, or was reduced if it was less than the set point. A minimum ventilation rate was set at 10% of full rate to create the minimum directional airflow: this was maintained during the night or under low incident solar radiation such as cloudy day.

Monitoring of environmental conditions

All temperature and CO_2 concentration data in the chamber was monitored individually every 10 seconds and averaged over 5-min intervals. The controller/data logger system, Green Kit 100 (ESD Co., Tokyo, Japan; cf. Table 1), was operated by the DL300 software (ESD Co.; cf. Table 1) under Windows. This set would be simple to manipulate, even if we have no knowledge of the technical programming.

Plants in the chamber

In order to test the availability of TGC for studying the effects of global warming on plant growth, three annuals species, *Chenopodium album* (C3), *Echinochloa crus-galli* (C4) and *Setaria viridis* (C4) were used as material.

Three experimental plots were prepared in the TGC in addition to the Control plot: at around 10 m (T2 plot, +2℃ warming) and 20 m (T4 plot, +4℃ warming) away from the air inlet. Each plot contained 18 containers, which were 60 cm long, 40 cm wide, and 24 cm deep.

Six containers for each species were placed in each of the five plots just prior to seeding. On 21 January, 1998, about 10 seeds were sowed at a 0.5-cm depth in square with spacing of 8 cm. After emergence of seedlings, a planting density of 100 plants per m^2 was realized by thinning all of them except one at each point. These containers were rotated within the same plot every 3 days in order to minimize such local environmental differences as light and air temperature. Sufficient water was irrigated early every afternoon through the growing season using a microjet sprinkler system suspended from the roof.

RESULTS

Temperature gradient in the chamber

The air temperature gradient in the chamber was satisfactorily created in every point throughout 1998 (Fig. 2). The lowest and the highest weekly mean air temperature at the air inlet were 0.3 and 26.5℃ in mid-January and early July, respectively, and at 25 m away from the air inlet they were 5.3 and 31.5℃, respectively, in the TGC. The air temperatures at the air inlet exceeded 23.0℃ from July to September except for the last week of July when they abruptly fell to 20.9℃. From September onward in 1998 the air temperatures fell gradually.

Annual mean air temperatures increased almost linearly from 14.3℃ at the air inlet to 19.2℃ at 25 m in the TGC (Fig. 2). Consequently, the warming of 1℃ every 5 m was satisfactorily realized with precision of ±0.2℃. Air temperatures were successfully regulated throughout all the seasons even in such a fine time step as half hour (Fig. 3).

Global warming conditions were well simulated at all plots in the chamber, independent of great seasonal and daily variations of ambient air temperature and incident solar radiation.

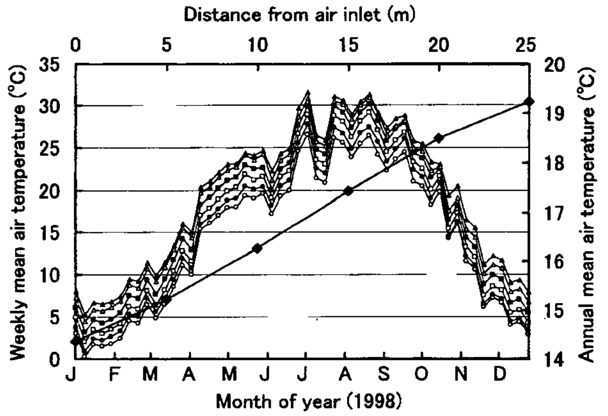

Fig. 2. Annual change of weekly mean air temperatures at every 5 m away from the air inlet in the TGC. Annual mean air temperatures are also indicated with the closed diamond (plotted on the right ordinate). Symbols: open circles, ambient; closed circles, 5 m; open squares, 10 m; closed squares, 15 m; open triangles, 20 m; closed triangles, 25 m from the air inlet.

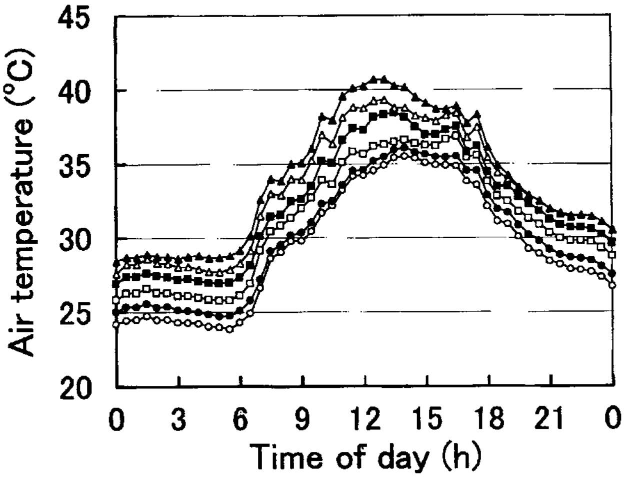

Fig. 3. Diurnal courses of half-hourly mean air temperatures at every 5 m away from the air inlet on 3 July in the TGC. Symbols: open circles, ambient; closed circles, 5 m; open squares, 10 m; closed squares, 15 m; open triangles, 20 m; closed triangles, 25 m from the air inlet.

CO_2 concentration in the TGC

The nighttime CO_2 concentrations were not always constant even in the TGC, but were higher nearer the air outlet. There were no substantial differences among the daytime CO_2 concentrations monitored at 0, 10, and 25 m away from the air inlet (Fig. 4). During the nighttime, on the other hand, the CO_2 concentrations were higher at 25 m away from the air inlet in the TGC, due to the gradual accumulation of respiratory CO_2 that was evolved from the material plants and soil.

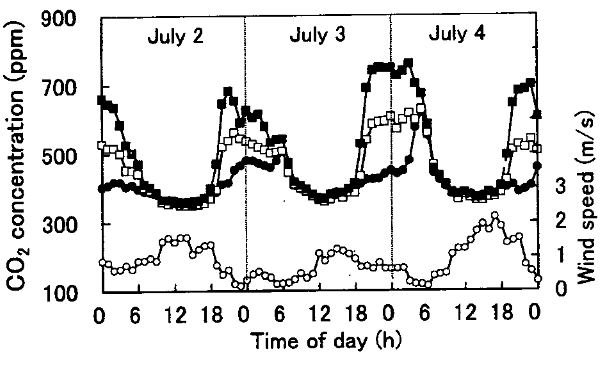

Fig. 4. Diurnal courses of half-hourly mean CO_2 concentrations and wind speed in the chamber. They were measured on 2~4 July at 10 and 25 m away from the air inlet. Symbols: open circles, wind speed; closed circles, ambient; open squares, 10 m away from the air inlet; closed squares, 25 m away from the air inlet.

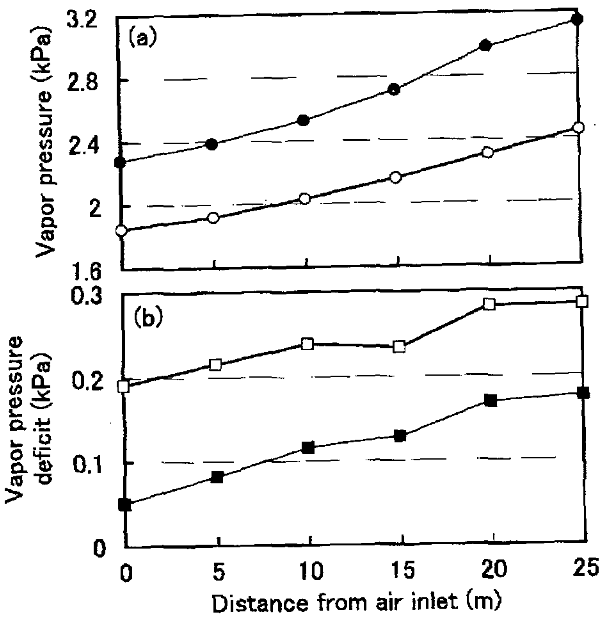

Fig. 5. Means of vapor pressure (a) and vapor pressure deficit (b) in the active growing season from 27 May to 7 June, illustrated for every 5 m from the air inlet in the chamber at daytime and at nighttime. Symbols: open circles, vapor pressure at daytime (6:00~18:00); closed circles, vapor pressure at nighttime (18:00~06:00); open squares, vapor pressure deficit (daytime); closed squares, vapor pressure deficit (nighttime).

Moisture condition

The mean vapor pressures were higher far from the air inlet at daytime (6:00~18:00) or nighttime (18:00~6:00) in the chamber (Fig. 5). The vapor pressure deficits (VPD) were larger, especially at daytime (Fig. 5a). The VPDs in the chamber was much higher during the daytime than those at night (Fig. 5b).

The relationship between incident solar radiation, ventilation rates and wind speed in the chamber

Wind in the chamber was always induced from the air inlet to the outlet by exhausting air by the four ventilators. The relationship between the wind speeds and the ventilation rates were investigated before the commencement of growth experiment without material plants. The wind speeds were measured with a hot-wire anemometer (Model 1000, Nihon Kagaku Co. Ltd., Tokyo, Japan) at heights of 0.4, 0.9, and 1.6 m above the ground at 5 m away from the air inlet. Wind increased from 15 to 60% for every 5% increase of ventilation rate (total capacity of the four ventilators was 485 m^3/min) (Fig. 6). The wind speeds were highest at 0.9 m and lowest at 1.6 m among the three heights. Mean wind speeds in the three heights increased approximately linearly with increasing percentage of ventilation rate, having the gradient of 0.0097 m/sec every percentage. At full ventilation rate (=100%), the maximum wind speed was less than 2 m/sec. However, the actual maximum ventilation rate did not exceed 60% even around noon under a clear and hot summer weather condition.

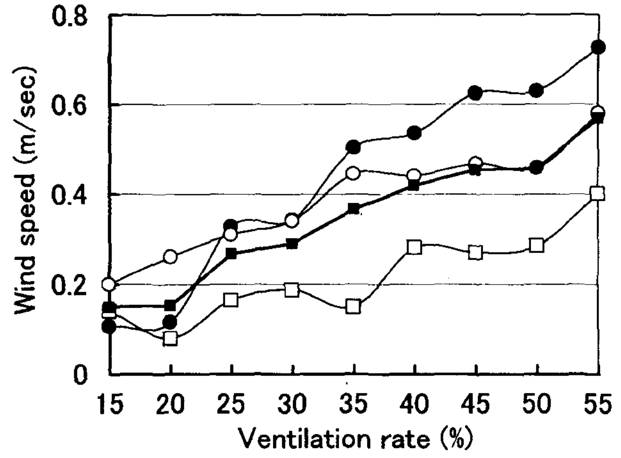

Fig. 6. The relationship between ventilation rate and wind speeds. Symbols: open circles, 40 cm above the ground; closed circles, 90 cm above the ground; open squares, 160 cm above the ground; closed squares, mean of three positions.

The hourly changes of ventilation rate were closely related to the instantaneous incident solar radiation in the chamber (Fig. 7) on a clear day when the maximum solar radiation

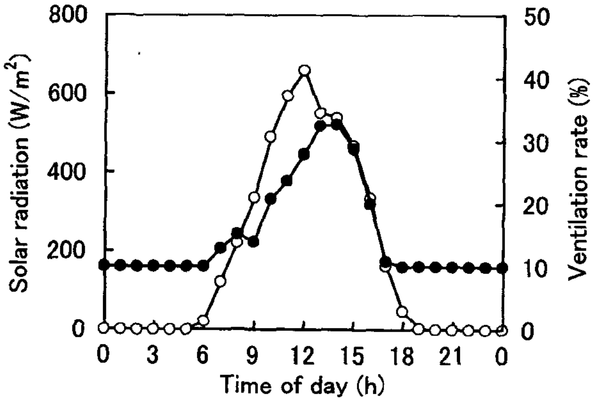

Fig. 7. Daily changes of solar radiation and ventilation rate in the chamber on a typical fine day (19 April, 1998). Symbols: closed circles, ventilation rate; open circles, solar radiation.

exceeded 600 W/m^2 around noon (19 April). The maximum ventilation rate was higher than 30%. However, incident solar radiation was not the sole determinant of ventilation rate. As shown in the inset of Fig. 6, the ventilation rates were always higher in the afternoon than in the morning under the same incident solar radiation.

DISCUSSION

We have successfully improved the reliability of the air temperature regulation in the TGC, independent of wide fluctuation of ambient air temperature. These high regulation abilities of the chamber were realized by the proportional-integral-differential (PID) algorithm. Although the ambient air temperatures greatly changed seasonally (cf. Fig. 2) or even daily (cf. Fig. 3), a linear temperature gradient of 5℃ from the air inlet to the outlet was always achieved; that is, the temperature gradient was 1℃ every 5 m in the chamber with precision of ±0.2℃. With respect to regulation accuracy of air temperatures, the chamber is much superior to similar facilities previously developed by Horie *et al.* (1995) and Okada *et al.* (1995), because the analog control system employed here enables us to set various rates of ventilation.

Experiments conducted in the TGC can provide tightly controlled temperatures, and their relatively low cost per enclosure allows for a high degree of replication. Although these facilities were suitable for a low stature plant or vegetation, they would be easily accessed to the plant at any location using a long transparent greenhouse tunnel already and widely utilized in agriculture. These facilities would allow us to utilize more widely with most suitable conditions to obtain both parameterization and validation data sets for models contributing to plant growth, species composition, and global carbon flux analysis.

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