Microclimate Prediction for Dynamic Greenhouse Climate Control

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Abstract. Greenhouse energy-saving and biocide reduction can be achieved through dynamic greenhouse climate control with computerized model-based regimes. This can be optimized when next to greenhouse macroclimate (i.e., the aerial environment) also, the crop microclimate is predicted. The aim of this article was to design and apply a simple deterministic microclimate model for dynamic greenhouse climate control concepts. The model calculates crop temperature and latent heat of evaporation in different vertical levels of a dense canopy of potted plants. The model was validated with data attained from experiments on dynamic or nondynamic (regular) controlled greenhouse cultivation. Crop temperature was with a 95% confidence interval of 2 °C or 2.4 °C for sunlit or shaded leaves, respectively, accurately predicted in a simple greenhouse with predefined climate set points. With a more dynamic greenhouse control also including assimilation lighting and screens, the prediction quality decreased but still had a 95% confidence interval of crop temperature prediction of 3.8 °C for sunlit leaves. Simulations showed that controlling greenhouse temperature according to the predicted crop temperature rather than according to the air temperature can save energy. Energy-saving is highest during winter and 12% energy saving was attained during January under Danish climate conditions.

During the last 20 years, several dynamic temperature regimes were designed for greenhouse energy-saving (e.g., Aaslyng et al., 1999; Bailey, 1985; Bailey and Seginer, 1989; Buwalda et al., 1999; Körner and Challa, 2003a; Seginer et al., 1994). In the early 1990s, a complete dynamic climate control concept was first developed (Aaslyng et al., 2003) and constantly further developed since then. The system aims at optimizing the greenhouse microclimate to ensure maximum net dry matter production, taking energy consumption into consideration (Aaslyng et al., 2003).

It is a component-based system, i.e., it consists of separate software building blocks that can be updated separately and new components can be added easily. Each component handles a biologic, physical, or environmental control task. Next to a component for dynamic temperature control, other climatic control components for, e.g., pests (Jakobsen et al., 2005), diseases (Körner and Holst, 2005), or supplementary assimilation light (Aaslyng et al., 2006; Körner et al. 2006), were developed.

Controlling greenhouse climate dynamically results in fluctuating greenhouse air

temperature. Greenhouse air temperature and crop temperature influence each other, but due to the different speed of warming up and cooling down, crop temperature can be higher or lower than greenhouse air temperature. As it is the crop temperature that influences crop growth and developmental processes, crop temperature rather than greenhouse air temperature needs to be controlled. In addition, the difference between air and crop temperature and the speed of temperature changes are the keys for many plant diseases (Körner and Challa, 2003b; Körner and Holst, 2005).

Although several approaches were presented to calculate crop temperature from the greenhouse macroclimate (Kempkes and Van de Braak, 2000; Wang and Deltour, 1999; Zhang et al., 1997, 2002), most climate controllers and regimes control the greenhouse air temperature rather than crop temperature. The few approaches to control crop temperature were designed for and tested with nondynamic (i.e., regular) greenhouse temperature regimes only. The few microclimate models for dynamic climate regimes (Boonen et al., 2000; Van Pee et al., 1998) were developed as black box models that are not generically usable. The aim of this work was therefore to develop and apply a simple generic deterministic microclimate model that can be used for dynamic greenhouse climate control. The model should be able to predict crop microclimate from a green-

house macroclimate (monitored by commercial climate-measuring equipment). In that way, greenhouse microclimate can be predicted by regular sensors that are located above the crop rather than distributing sensors within the crop.

A model is presented that describes the crop microclimate in a vertical transect of the crop canopy. The model was validated with experimental data from dynamic and regular climate regimes. In a final simulation study, comparisons were made on the effects on energy consumption and crop microclimate by controlling greenhouse temperature either based on ambient greenhouse temperature (belonging to macroclimate) or by crop temperature (belonging to the microclimate) calculated with the presented microclimate model.

Materials and Methods

Model development. Crop temperature (T_c , K) in different canopy layers (z) was calculated by integrating absorbed irradiative net fluxes ($R_{n,a}$, $W \cdot m^{-2}$), boundary layer and stomata resistances (r_b and r_s , respectively, $s \cdot m^{-1}$), and vapor pressure deficit at the leaf surface (VPD_s , kPa) in the canopy. The extinction of short-wave radiation as it passes through the canopy to heights z was calculated with the Lambert-Beer's law; z was a function of the leaf area index (LAI) and estimated for three vertical positions in the canopy according to the Gaussian three-point integration procedure (Goudriaan and Van Laar, 1994):

$$z_{(1,2,3)} = \begin{cases} 0.11 \cdot LAI \\ 0.50 \cdot LAI \\ 0.89 \cdot LAI \end{cases} \quad [1]$$

Crop temperature, T_c , was calculated according to Stanghellini (1987):

$$T_c(z) - T_a = \frac{\frac{1}{\rho_a c_p} (r_b(z) + r_s(z)) R_{n,a}(z) - \frac{1}{\gamma} VPD_s(z)}{1 + \frac{\delta}{\gamma} + \frac{r_s(z)}{r_b(z)} + \frac{1}{\rho_a c_p / 4\sigma T_a^3} (r_b(z) + r_s(z))} \quad [2]$$

with greenhouse air temperature (T_a , K), air density (ρ_a , $g \cdot m^{-3}$), Stefan-Boltzmann constant (σ , $W \cdot m^{-2} \cdot K^{-4}$), specific heat capacity of the air (c_p , $J \cdot g^{-1} \cdot K^{-1}$), the psychrometric constant (γ , $Pa \cdot K^{-1}$), and the slope between saturated vapor pressure and greenhouse air temperature (δ , $Pa \cdot K^{-1}$). Latent heat of evaporation (λE , $W \cdot m^{-2}$) in different canopy layers was calculated with Eq. [3]:

$$\lambda E(z) = \left(\frac{\frac{\delta}{\gamma} R_{n,a}(z) + \frac{\rho_a c_p}{\gamma} \left(\frac{1}{r_b(z)} + \frac{1}{\rho_a c_p / 4\sigma T_a^3} \right) VPD_s(z)}{1 + \frac{\delta}{\gamma} + \frac{r_s(z)}{r_b(z)} + \frac{1}{\rho_a c_p / 4\sigma T_a^3} (r_s(z) + r_b(z))} \right) \quad [3]$$

Too high potential λE can result in a higher transpiration than plants can handle and then water loss may exceed water uptake

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(Körner and Challa, 2003b). In the opposite case when λE becomes negative, dew will be formed on leaves and other tissues that can lead to plant diseases.

Leaf net absorption of short- and long-wave radiation ($R_{n,a}$, $W \cdot m^{-2}$) was calculated from incoming solar short wave radiation to the crop (Q , $W \cdot m^{-2}$), a factor for leaf absorbance of short-wave radiation (a) and the long-wave radiation exchange between the leaves and the greenhouse (L_n , $W \cdot m^{-2}$) (Yu et al., 2001):

$$R_{n,a}(z) = aQ(z) + L_n(z) \quad [4]$$

Long-wave radiation exchange was calculated for the different horizontal positions in the canopy in accordance to equation developed by Ross (1975). The long-wave radiation exchange was separated into exchanges at the upper and the lower leaf surfaces (L_u , L_d , $W \cdot m^{-2}$, respectively):

$$L_n(z) = L_d(z) + L_u(z) \quad [5]$$

$$L_d(z) = L_d(0) - \tau_d(z)(L_d(0)) \quad [6]$$

$$L_u(z) = L_u(0) - \tau_u(z)(L_u(0)) \quad [7]$$

with penetration functions for downward and upwards long-wave radiation (τ_d and τ_u , respectively); $L_d(0)$ ($W \cdot m^{-2}$), and $L_u(0)$ ($W \cdot m^{-2}$) are radiation exchanges from lower and upper leaf surfaces at a crop level LAI of 0 (i.e., canopy top). The $L_d(0)$ and $L_u(0)$ values were calculated from the long-wave radiation exchange between crop temperature at crop level LAI of 0 (T_{c0} , K) or greenhouse surface temperatures (T_g , K), and the greenhouse cover or screen temperature (T_r , K), the Stefan-Boltzmann constant, and emissivities of crop surface, greenhouse cover or screen, and the remaining greenhouse surfaces (ϵ_{c0} , ϵ_r , ϵ_g , respectively, $W \cdot m^{-2}$). The effective emissivities between the surfaces ($\epsilon_{c0,r}$, $\epsilon_{c0,g}$, $W \cdot m^{-2}$) were calculated with a simple relation assuming large parallel surfaces according to Bot and Van de Braak (1995) (Eq. [10]). Greenhouse surface temperatures include heating pipes, tables, soil, and others. For simulations, the initial value of T_{c0} was assumed equal to greenhouse air temperature; in later simulation steps, the calculated crop temperature of the preceding simulation step was used:

$$L_d(0) = \epsilon_{c0,r} \cdot \sigma \cdot (T_{c0}^4 - T_r^4) \quad [8]$$

$$L_u(0) = \epsilon_{c0,g} \cdot \sigma \cdot (T_{c0}^4 - T_g^4) \quad [9]$$

$$\begin{aligned} \epsilon_{c0,r} &= (1/\epsilon_{c0} + 1/\epsilon_r)^{-1} \\ \epsilon_{c0,g} &= (1/\epsilon_{c0} + 1/\epsilon_g)^{-1} \end{aligned} \quad [10]$$

When artificial assimilation light was used, a term for absorbed heat energy and

long-wave radiation produced by the lamps (E_{AL} , $W \cdot m^{-2}$) was added to Eq. [8]:

$$L_d(0) = \epsilon_{c0,g} \cdot \sigma \cdot (T_{c0}^4 - T_r^4) - E_{AL} \quad [11]$$

The penetration function for downward long-wave radiation, τ_d , as a function of z was attained by fitting data published by Ross (1975) (fitted parameters c , d , and e : -0.008 , -0.857 , 0.046 , respectively; standard error of the estimate 0.005). Because z is a function of the LAI, τ_d decreased with increasing LAI:

$$\tau_d(z) = \exp\left(c + d \cdot z + (e \cdot z)^2\right) \quad [12]$$

The penetration function for upwards long-wave radiation, τ_u , was assumed similar to τ_d . T_r was either calculated from the four variables greenhouse air temperature, effective sky temperature (Yu et al., 2001), outside temperature, and wind speed outside the greenhouse (De Zwart, 1996); or when available, measured data were used to predict T_r . T_g was either assumed to be the same as greenhouse air temperature or measured data were used.

Stomata resistance was calculated from relative humidity at leaf surface (RH_l , %), minimum stomata resistance to water vapor at light compensation ($r_{s,min}$, $mol \cdot m^{-2} \cdot s^{-1}$), CO_2 partial pressure at the leaf surface (C_l , $\mu mol \cdot mol^{-1}$), an empiric coefficient (j), leaf net assimilation rate (P_{nl} , $\mu mol \cdot m^{-2} \cdot s^{-1}$), and atmospheric pressure (θ , Pa) as proposed for potted roses (Ball et al., 1987; Kim and Lieth, 2003); k is the conversion factor from [$m^2 \cdot s \cdot mol^{-1}$] to [$s \cdot m^{-1}$] with 0.025 (Jones, 1992):

$$r_s(z) = \left(r_{s,min} + j \cdot P_{nl}(z) \frac{RH_l}{C_l(z)/\theta} \right)^{-1} \cdot k \quad [13]$$

Leaf net photosynthesis was attained by fitting the negative exponential light response curve (Thornley, 1976) with leaf photochemical efficiency (α_l , [$mol \cdot CO_2$]·[$mol \cdot photons$] $^{-1}$) and maximum leaf net photosynthesis ($P_{nl,max}$, $\mu mol \cdot m^{-2} \cdot s^{-1}$) for the different canopy levels z according to the photosynthetic photon flux (I_{PPF} , $\mu mol \cdot m^{-2} \cdot s^{-1}$):

$$P_{nl}(z) = P_{nl,max} \cdot \left(1 - \exp\left(\frac{-\alpha_l \cdot I_{PPF}(z)}{P_{nl,max}}\right) \right) \quad [14]$$

Absorbed I_{PPF} fluxes were calculated separately for diffuse and direct radiation and as a function of z (Van Kraalingen and Rappoldt, 1989). Leaf photochemical efficiency, α_l , and $P_{nl,max}$ were calculated based on biochemical leaf photosynthesis models (Farquhar and Von Caemmerer, 1982; Farquhar et al., 1980) and approaches of Gijzen (1994) as shown by Körner (2004). The boundary layer resistances (r_b , $s \cdot m^{-1}$) for leaves in different crop levels z were attained from the dimensionless Nusselt number (Nu) and the thermal diffusivity of air (χ , $m^2 \cdot s^{-1}$) as

proposed for potted chrysanthemums (Yang, 1995). The Nu number was calculated from the dimensionless Grashof (Gr) and Reynolds (Re) numbers (Stanghellini, 1987):

$$r_b(z) = (\chi \cdot Nu(z))^{-1} \quad [15]$$

$$Nu(z) = 0.37 \cdot \left(Gr(z) + 6.92 \cdot Re(z)^2 \right)^{0.25} \quad [16]$$

$$Re(z) = u(z) \cdot l / \nu \quad [17]$$

$$Gr(z) = g \cdot \beta \cdot l^3 / \nu^2 \cdot (T_c(z) - T_a) \quad [18]$$

with air velocity (u , $m \cdot s^{-1}$), the characteristic dimension of the leaf surface (l , m), the kinematic viscosity of air (ν , $m^2 \cdot s^{-1}$), acceleration resulting from gravity (g , $m \cdot s^{-1}$), and the coefficient of thermal expansion (β , K^{-1}).

Greenhouse experiments. Two experiments with potted roses were carried out. Expt. 1 was conducted with a 24-h dynamic temperature regime, i.e., temperature was only dynamic within 24 h and set points were the same for each 24 h. Expt. 1 was a short-term experiment of 5 weeks (8 Nov.–15 Dec. 2004). Roses (*Rosa*, ‘Vanilla Charming Parade’) were planted in black plastic pots (8-cm high, 10-cm diameter) filled with a commercial peat mix and were then placed on an ebb and flow table in a research greenhouse compartment (25 m^2) at the Danish Institute of Agricultural Sciences (Slagelse, Denmark, 55°18′N). Plants were placed with a spacing of 10 cm to all sides. Plants were allowed to grow naturally (no pinching), but plant height was kept at 20 cm (from pot edge) by periodic cutting with electric scissors. Within each 24-h period, temperature was set to 10, 20, or 24 °C: 10 °C (0800–1159 HR; 2000–2359 HR), 20 °C (1200–1759 HR; 0000–0559 HR), and 24 °C (0600–0759 HR; 1800–1959 HR). As a result of the relatively large greenhouse surface in relation to the plant canopy, humidity levels were expected to be much lower than in commercial size greenhouses. To attain humidity levels like in commercial practice, the relative humidity (RH) set point was 100% (i.e., neither heating nor ventilation for dehumidification was used). In addition, a fogging and ventilation system located under the tables distributed water vapor in the greenhouse when RH was lower than 85%. With that procedure, RH levels with an average of 74% (ranging between 52% and 100% RH, standard deviation 15.3% RH) were attained. Only during some periods, RH was close to 100% and no incidences with fungi such as *Botrytis* were observed before determination of the experiment.

Climate was controlled with a commercial greenhouse climate computer (LCC1200; DGT Volmatic, Odense, Denmark). The vents were closed throughout the complete experiment. Pipe heating was used. An energy-saving screen (LS10; Ludvig Svensson,

Kinna, Sweden) was closed during night between 1900 and 0600 HR. No assimilation light was used. Greenhouse macroclimate (RH and air temperature) was measured with a commercial climate measuring box (0.8 m above the crop) equipped with a capacitive hygrometer and a PT500 thermometer (Senmatic, Sønderød, Denmark). Microclimate was measured in the two crop levels z_1 and z_3 . In both levels, leaf surface temperature was measured with two IR thermocouples (IRTS-P5; Apogee Instruments, Logan, UT); RH and temperature close to the leaf surfaces (from 3 to 5 cm distance) were measured with a capacitive hygrometer and a PT100 thermometer, respectively (Hygroclip S3; Rotronic, Basserdorf, Switzerland). Because z_1 and z_3 were a function of the LAI (Eq. [12]), the measuring equipment was adjusted weekly. PPF density (I_{PPF} , $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) was measured with two line quantum sensors (LI-190SA; LI-COR, Lincoln, Neb.). All data were continuously recorded and logged with 1-min averages in two computer-controlled data loggers (DT 600 with DeLogger 4; DataTaker, Rowville, Australia).

In Expt. 2, temperature was controlled by the IntelliGrow system, a complex control regime (Aaslyng et al., 2003). Expt. 2 compared the microclimate attained with a regular and a dynamic temperature regime. Within the dynamic regime, temperature could fluctuate differently between days; set points were fixed for the regular regime (Table 1). Expt. 2 was a long-term experiment (5 Sept. 2001–27 May 2002) with a total of seven batches of potted roses (*Rosa*, 'Vanilla Charming Parade') grown sequentially until plants had reached the commercial

harvest stage. Young potted roses were placed to a density of 40 plants·m² on ebb and flow tables (7 m²) in four greenhouse compartments (66 m² each) of the Royal Veterinary and Agricultural University (Copenhagen, Denmark, 55°41'N).

In Expt. 2, outdoor climate was measured by a standard weather station. Greenhouse macroclimate as air temperature (10K3MCD1; BetaTHERM, Galway, Ireland), CO₂ concentration (from 0 to 2000 $\mu\text{mol}\cdot\text{mol}^{-1} \pm 10 \mu\text{mol}\cdot\text{mol}^{-1}$) (URAS 4; Hartmann & Braun, Frankfurt, Germany), air humidity (from 0% to 100% RH, $\pm 1.5\%$) (Hygroclip S; Rotronic, Basserdorf, Switzerland), global radiation (CM-11 pyranometer; Kipp and Zonen, Delft, The Netherlands), and I_{PPF} (G1125–06; Hammamatsu, Japan; and LI-190SA; LI-COR) were measured and computer-controlled (LCC1200; DGT Volmatic, Odense, Denmark). The climate set points were generated with the IntelliGrow software (Aaslyng et al., 2003) that was implemented in another computer and sent to the LCC1200 in a 10-min time interval (Aaslyng et al., 2005). Set points were determined from macroclimate measurements and either calculated dynamically or by the regular regime (Table 1). Greenhouse microclimate as temperature (four evenly distributed type T thermocouples and one infrared [IR] thermocouple) (Sensycon; Hartmann & Braun, Frankfurt, Germany; Exergen IR, Watertown, Mass., respectively), I_{PPF} (G1125–06; Hammamatsu, Japan; and LI-190SA; LI-COR), and global radiation (CM-3 pyranometer; Kipp and Zonen) were measured on each table on sunlit leaves only (position z_1). Greenhouse com-

partments roof temperatures were measured with thermistors (100K6MCD1; BetaTHERM, Shrewsbury, Mass.) on the north and on the south side of each greenhouse compartment. The same type of thermistors were also used to measure soil temperature and pipe heating in- and outlet temperatures. All data were continuously measured, averaged over 5 min, and stored in a data logger (CR10X; Campbell Scientific, Logan, Utah). Supplementary lighting was used (see Table 1). Ten high-pressure sodium lamps (SON-T, 400 W; Philips, Eindhoven, The Netherlands) were installed in each greenhouse compartment (0.152 lamps per m²). Next to visible radiation, the high-pressure sodium lamps produced 80 W IR radiation and 202 W heat plus an additional 36 W produced by the generator. For simple estimation of long-wave radiation exchange with the upper leaf surface (Eq. [11]), it was assumed that 50% of the heat production reached the crop top surface.

Simulating greenhouse microclimate. The previously described model was programmed in the simulation software environment MATLAB (version 7.2; The MathWorks; Lowell, Mass.). The model's sensitivity was tested with artificially created climate data (Table 2). Simulations were performed with measured greenhouse macroclimate data (Expts. 1 and 2) using a 5-min simulation time step.

Climate control simulation study. For a simulation study, a greenhouse climate and control simulator (GCCS) (Körner et al., 2004) was connected to the presented microclimate model. The GCCS calculated greenhouse macroclimate for a standard 1-ha Venlo-type greenhouse with a single glass

Table 1. Overview of the set points used in the dynamic climate regime in Expt. 2 (Lund et al., 2006).

Parameter		Strategy	Set points and limits	
			Minimum	Maximum
Climate strategies for the dynamic climate				
Day temperature	Set point is calculated by the use of a leaf photosynthesis model	15 °C	30 °C	
	Natural heating can increase the temperature to a higher value than the set point			
Night temperature	Set point kept constant at the lowest acceptable limit for the actual crop	15 °C	30 °C	
	Temperature decrease passive from the day temperature to the set point; vents were not used during the nights			
Vent	Only used to protect the plants from high temperatures; a fixed set point depending on the actual crop		Temperature >30°	
	Kept closed as much as possible to conserve energy and make CO ₂ injection possible			
CO ₂	Set point calculated by the use of a leaf photosynthesis model to maximize photosynthesis to the actual temperature and irradiance; only injection with closed vents	350 μmol·mol ⁻¹	2000 μmol·mol ⁻¹	
Screen set point	The economic optimum time for the use of screens was determined using a thermal screen simulation system (Aaslyng et al., 1999)			
Climate strategies for the traditional climate				
Temperature	Controlled by a day (19 °C) and night (21 °C) temperature and a ventilation limit (22 °C)	19 °C	22 °C	
CO ₂	Only injection with closed vents	350 μmol·mol ⁻¹	600 μmol·mol ⁻¹	
Screens	Off in the morning when the inside short-wave radiation >2 W·m ⁻² ; on in the evening when inside short-wave radiation <8.5 W·m ⁻²			
Climate strategies for the dynamic and traditional climate				
Supplementary lighting	Applied between 5 Sept. 2001 and 25 Feb. 2002 from 0600 to 2300 HR; on when the outside radiation was <39 W·m ⁻² ; off when the outside radiation was >120 W·m ⁻²	39 W·m ⁻²	120 W·m ⁻²	

cover (transmission for diffuse radiation of 78.5%), energy-saving screen (LS10; Ludvig Svensson, Kinna, Sweden), and assimilation light. The Danish 1-year reference climate data file (Design Reference Year [DRY]; Lund, 1995) was input to the GCCS. Control inputs were climate set points for heating, ventilation, CO₂ concentration, and screening. Those were generated by a set point generator program (SPG) and provided to the GCCS by data file-sharing in a 5-min interval. This simulation study compared the effect on energy consumption and the micro-climate factors dew formation and crop temperature of 1) commonly used greenhouse climate control with greenhouse air temperature with 2) greenhouse climate control with crop temperature, meaning the SPG either used greenhouse air temperature or crop temperature as the basis for set point calculations. Two temperature regimes were tested: 1) regular temperature set points for day and night with a 1 °C margin between heating and ventilation, and 2) a dynamic 24-h temperature integration regime in which temperature could fluctuate freely between the calculated heating and ventilation temperatures (Table 3). Both regimes were thoroughly described in Körner et al. (2004).

Results

Model presentation. The model predicted a strong dependency of crop temperature to short-wave radiation and greenhouse air temperature. The effect of short-wave radiation decreased with increasing LAI (i.e., the effect on z_1 leaves was higher than on z_2 or z_3 leaves) and decreased with increasing greenhouse air temperature (Figs. 1 and 2). The difference between crop temperature and cover temperature increased with an increasing gradient between inside and outside greenhouse temperature. In this situation, leaves exchange less long-wave radiation if they are situated in lower canopy levels and therefore lose less energy than leaves in higher levels. This leads to temperature difference between z_1 and z_3 leaves. Increasing the short-wave radiation had the opposite effect (Figs. 1 and 2). Strong effects of short-wave radiation on potential evaporation could be observed, too. When short-wave radiation was high, λE decreased with increasing LAI (Fig. 3). At darkness, λE reacted opposite to that, and when RH was very high, negative λE values could be observed in z_1 leaves, i.e., condensation on the plant surface and an increasing risk of diseases (Fig. 3). The effects of short-wave radiation on both leaf temperature and dew formation (i.e., negative λE) decreased with increasing LAI (Figs. 3 and 4). Those effects were strongest when short-wave radiation was high, because the position of z in the canopy was not constant but defined by LAI (Eq. [1]).

Greenhouse experiments. The model was able to predict leaf surface temperature well for both z_1 and z_3 leaves when temperature fluctuations were preprogrammed (Expt. 1)

Table 2. Simulations settings for climate control study with simulation range (range) and simulation time steps (step unit).

	Greenhouse air temperature (°C)	Relative humidity (%)	Global radiation (W·m ⁻²)	Leaf area index (m ² ·m ⁻²)
Range	0–40	50–100	0–200	0–4
Step unit	1	10	20	0.1

Table 3. Climate settings for simulation study for regular and dynamic (24-h temperature integration) climate control: ventilation temperature (T_v), heating temperature (T_h), relative humidity (RH), CO₂ concentration.

	Regular	Dynamic
T _v (°C)	19	Dynamic, maximum 23.0
T _h (°C)	18	Dynamic, minimum 15.5
RH (%)	85	85
CO ₂ (μmol·mol ⁻¹)	400	400
Screen (off-on)	Energy-saving screen was unfolded when global outside radiation was 0 W·m ⁻²	
Assimilation light (W·m ⁻²)	25 W·m ⁻² (high-pressure sodium lamps) when global outside radiation was lower than 125 W·m ⁻² , a maximum of 20 h during each 24-h period	
Leaf area index	1.5

Fig. 1. Simulated crop temperature in three canopy positions (z_1 [—], z_2 [---], and z_3 [···]) as a function of greenhouse air temperature for four inside global radiation levels: (A) 0 W·m⁻², (B) 40 W·m⁻², (C) 80 W·m⁻², and (D) 160 W·m⁻². All other factors were set constant: leaf area index 2, relative humidity 80%, outside air temperature 15 °C, CO₂ 350 μmol·mol⁻¹ (see Table 2).

Fig. 2. Simulated crop temperature at 15 °C (—), 25 °C (---), and 35 °C (···) air temperature as a function of the canopy level z at (A) 0 W·m⁻² or (B) 160 W·m⁻² global radiation inside the greenhouse. All other factors were set constant: LAI 1.5, RH 80%, outside air temperature 15 °C, CO₂ 350 μmol·mol⁻¹ (see Table 2).

Fig. 3. Simulated latent heat of evaporation at 15 °C (—), 25 °C (---), and 35 °C (···) air temperature as a function of the canopy level z at 0 $\text{W}\cdot\text{m}^{-2}$ (gray lines) or 160 $\text{W}\cdot\text{m}^{-2}$ (black lines) global radiation inside the greenhouse at (A) 70% or (B) 100% relative humidity. All other factors were set constant: leaf area index 1.5, outside air temperature 15 °C, CO_2 350 $\mu\text{mol}\cdot\text{mol}^{-1}$ (see Table 2).

Fig. 4. Crop temperature at different inside greenhouse global radiation levels of (A, B) 0 $\text{W}\cdot\text{m}^{-2}$ and (C, D) 160 $\text{W}\cdot\text{m}^{-2}$ as a function of the canopy level z and at (A, C) four different leaf area indexes (LAI 0.1 [—], LAI 1 [---], LAI 2 [· · ·], LAI 3 [· · · ·]) and (B, D) three different canopy levels (z_1 [—], z_2 [---], and z_3 [· · ·]). All other factors were set constant: greenhouse air temperature 20 °C, relative humidity 80%, outside air temperature 15 °C, CO_2 350 $\mu\text{mol}\cdot\text{mol}^{-1}$ (see Table 2) LAI indicates leaf area index.

(Fig. 5). However, periodically, some incongruence occurred. The natural heating up and cooling down of the greenhouse (no heating) was well predicted (high and low peaks). Only when pipe heating was used to heat up the greenhouse after a cool period did the model disagree with the measurements. However, the difference in predicted and measured temperature was noteworthy only during these periods.

In situations when the greenhouse climate was more actively controlled than in Expt. 1, i.e., also with artificial lighting, screens, and vents (Expt. 2), the model had to be adjusted to these circumstances. When energy exchanges with the lamps

and the screen were added to the model, greenhouse microclimate was well predicted (Fig. 6).

The model's high quality is expressed by the narrow 95% confidence interval in Expt. 1 that was ≈ 2 °C for z_1 leaves and 2.4 °C for z_3 leaves (Fig. 7). Simulated and measured crop temperature differed only in some cases by more than 2 °C. In more than 60%, predictions were within a 1 °C range (60% and 66% for z_1 and z_3 , respectively) (Fig. 8). The 95% confidence interval in Expt. 2 was much higher than in Expt. 1 (i.e., 3.8 °C, Fig. 9).

Climate control. The simulation study with the dynamic climate regime showed a closer fit between microclimate and set points

when greenhouse climate was controlled to crop temperature (rather than to greenhouse air temperature) (Table 4). Because results with the regular climate regime were similar to the dynamic regime, no further data are presented. Greenhouse air temperature control resulted in warmer plants than wanted throughout the year. The difference in crop temperature between air and crop temperature control was most eminent in winter. In January, leaf temperature in all three vertical crop levels was ≈ 1 °C higher with greenhouse air temperature control than with crop temperature control. For that, unnecessary heating energy was used (Table 4). Shifting from greenhouse air temperature control to crop temperature control with the presented model could save more than 12% energy in January. Energy-saving percentages decreased toward summer. Only a small positive effect of crop temperature control on dew formation could be observed (Table 4).

Discussion

Microclimate prediction models applicable for model-based greenhouse climate control are scarce. We therefore aimed at creating a simple microclimate model with the prediction quality demanded in dynamic greenhouse climate control. Quality assessment of a crop microclimate model quality includes mainly five major points: 1) general fit between real and simulated crop temperature, 2) prediction quality of high and low temperature peaks, 3) predicting the difference in temperature fluctuation speed between air and plants, 4) predicting the vertical microclimate differences in the crop canopy, and 5) prediction of the horizontal microclimate differences in the greenhouse.

The general fit between simulated and measured crop temperature was satisfying. However, the model yielded in some biased predictions of leaf temperature, with the largest over- and underestimations during warming up of the greenhouses through pipe heating. Estimating leaf temperature was however successful when temperature was not controlled. The discrepancies between measured and simulated leaf temperatures in some periods can probably be explained by the complexity of the greenhouses the measurements were taken in. In addition, microclimate predictions with the complete dynamic regime and with more active climate control and assimilation light (Expt. 2) had a lower quality. This could probably be explained through strong simplifications in the model construction for, e.g., artificial assimilation light or heating pipes. Also, greenhouse size, position of the heating pipes, table structures and positions, and table distances from heating pipes, and so on, differ between greenhouses and the greenhouse equipment, which was only approximated and roughly implemented in the model. Because greenhouses in northern

Fig. 5. Measured (black) and simulated (gray) crop temperature for (A) z_3 leaves and (B) z_1 leaves during 10 d of Expt. 1 (day 335 to day 344 of the year). The position of the indicated day numbers is at 1800 HR.

Fig. 6. Measured (black) and simulated (gray) pot-rose crop temperature with data from Expt. 2 for 40 d (A) between day of the year 108 and 148 and day of year 147 (B) for a dynamic climate regime with the IntelliGrow system.

Europe are often equipped with assimilation lights, a better implementation of those (and other equipment) will strongly improve the quality of the model and its potential for the use in practice. There are many parameters that could improve the models prediction quality, e.g., heat transfer calculations between heating pipes and tables, tables and pots, and plants and side walls. Other parameters such as the influence of water on the tables on crop microclimate, the thickness of leaves, or the compactness of the plants was not taken into account either. Furthermore, assuming that the sum of all nonliving greenhouse material temperatures (T_g) is the same as greenhouse air temperature may not be correct, but to include the complete interior of the greenhouse involves complex calculations and model adjustments. Different materials can either be warmer or colder than the air (depending on greenhouse climate, material, and humidity content). Because we

aimed at developing a simple and generic microclimate prediction model, we judge the simplifications that were made as reasonable for an overall estimation.

With only a few adjustments, the model was able to predict greenhouse microclimate well in different greenhouses such that the 95% confidence interval was 2 °C or 3.8 °C. Because the model was able to predict high and low peaks very well and because this is the most important quality criterion, the incongruence in the general fit are acceptable within its low range. Also, the slow reaction of the crop tissue to temperature fluctuations was well predicted (Fig. 6). The last criterion, however, was not implemented in the model nor was it tested. Calculating the horizontal microclimate differences in greenhouses demands a complex three-dimensional model and this is out of scale of the present research. However, our experiments were done in small research

Fig. 7. Simulated versus measured leaf temperature for (A) z_1 leaves and (B) z_3 leaves in Expt. 1 with 95% nonsimultaneous confidence intervals: (A) ± 1.99 °C and (B) ± 2.43 °C.

facilities that are very different from commercial-sized greenhouses that can measure several hectares. The climate in large greenhouses is probably more uniform and a general model, like the one presented here, could probably be applied much easier under such conditions. The present model was demonstrated through sensitivity analysis and through model validation with data from two different research greenhouses. Although the accuracy of the predictions differed in the two greenhouse experiments, these differences were small.

The presented microclimate model has the potential for being generic. A simulation case study showed that using this model to predict crop microclimate is a promising alternative to greenhouse air temperature control and may be used for model-based dynamic control regimes (Aaslyng et al., 1999; Bailey, 1985; Bailey and Seginer, 1989; Buwalda et al., 1999; Körner and Challa, 2003a; Seginer et al., 1994) or for the concept of optimal greenhouse climate control (Gal et al., 1984). Because 10% energy is saved by a 1 °C lower greenhouse temperature (Tantau, 1998), heating demand and therefore energy consumption can strongly decrease when using this microclimate model for crop temperature control. This was also shown in the simulation study. Controlling the greenhouse climate more specific to the coldest crop layer (rather than using an average crop temperature as the control)

Fig. 8. Frequency diagrams of absolute deviations from simulated to measured leaf temperature in Expt. 1 for (A) z_1 and (B) z_3 and (C) Expt. 2.

Fig. 9. Simulated versus measured leaf temperature for z_1 leaves during 40 d in Expt. 2 with the 95% nonsimultaneous confidence interval (± 3.8 °C).

and designing a regime for crop diseases can improve the concept strongly. Condensation could be reduced and therefore also the risk for fungi diseases (Huber and Gillespie, 1992; Körner and Holst, 2005). For the optimal use of that, however, the previously mentioned three-dimensional microclimate prediction is needed.

It can thus be concluded that the presented model is useful for microclimate predictions, although its robustness remains to be tested for additional greenhouse constructions and locations and different plant species. Strong improvements to the model would be a three-dimensional greenhouse macroclimate model that could be used to predict horizontal greenhouse microclimate differences.

Table 4. Weekly averages of air temperature, crop temperature, and sums for dew; and energy consumption in three canopy levels z for simulations with dynamic climate control (see Table 3) with air temperature or crop temperature control (ATC or LTC) and standard deviation.^a

Week	Canopy level	Variable							
		Air temperature (°C, mean)		Crop temperature (°C, mean)		Sums for dew ^b (minutes)		Energy consumption (total sum, MJ·m ⁻²)	
		ATC	LTC	ATC	LTC	ATC	LTC	ATC	LTC
1	z_1	18.1 $\pm$ 2.7	16.9 $\pm$ 1.7	18.9 $\pm$ 3.1	17.9 $\pm$ 2.5	180	180	49	43
	z_2			19.2 $\pm$ 2.9	18.1 $\pm$ 2.1	45	40		
	z_3			19.6 $\pm$ 2.6	18.5 $\pm$ 1.7	0	0		
5	z_1	18.0 $\pm$ 2.9	16.9 $\pm$ 1.7	19.3 $\pm$ 3.1	18.3 $\pm$ 2.5	130	125	43	39
	z_2			19.4 $\pm$ 3.0	18.3 $\pm$ 2.0	50	45		
	z_3			19.7 $\pm$ 2.8	18.6 $\pm$ 1.7	0	0		
9	z_1	18.1 $\pm$ 2.9	17.2 $\pm$ 2.3	20.6 $\pm$ 4.2	19.8 $\pm$ 4.2	90	85	35	32
	z_2			20.1 $\pm$ 3.3	19.3 $\pm$ 3.1	20	10		
	z_3			20.2 $\pm$ 3.1	19.4 $\pm$ 2.7	0	0		
13	z_1	18.4 $\pm$ 3.2	17.9 $\pm$ 2.9	20.8 $\pm$ 5.2	20.4 $\pm$ 5.2	100	100	25	24
	z_2			20.1 $\pm$ 4.0	19.7 $\pm$ 3.9	20	35		
	z_3			20.2 $\pm$ 3.6	19.8 $\pm$ 3.5	0	0		

^aThe target temperature range was from 18 to 19 °C.

^bDew was attained when the latent heat of evaporation (λE , W·m⁻², Eq. [3]) was negative.

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Notation

a	Leaf absorbance of short-wave radiation	P_{nl}	Leaf net assimilation rate
α_l	Leaf photochemical efficiency	$P_{nl,max}$	Maximum leaf net photosynthesis
β	Coefficient of thermal expansion	λ	Psychrometric constant
C_l	CO ₂ partial pressure at the leaf surface	Q	Incoming solar short-wave radiation to the crop
c_p	Specific heat capacity of the air	RH_l	Relative humidity at leaf surface
δ	Slope between saturated vapor pressure and air temperature	RH	Relative humidity of air
ϵ_{c0}	Emissivity of crop surface	r_b	Boundary layer resistance
ϵ_r	Emissivity of greenhouse cover or screen	r_s	Stomata resistance
ϵ_g	Emissivity greenhouse surfaces	$r_{s,min}$	Minimum stomata resistance
$\epsilon_{c0,r}$	Effective emissivities between crop and cover or screen	$R_{n,a}$	Absorbed irradiative net fluxes
$\epsilon_{c0,g}$	Effective emissivities between crop and greenhouse surfaces	Re	Reynolds number
E_{AL}	Heat energy and long-wave radiation produced by the lamps	ρ_a	Air density
g	Acceleration resulting from gravity	SPG	Set point generator program
$GCCS$	Greenhouse climate and control simulator	σ	Stefan-Boltzmann constant
Gr	Grashof number	T_a	Air temperature
I_{PPF}	Photosynthetic photon flux density	T_c	Crop temperature
k	Conversion factor from [m ² ·s·mol ⁻¹] to [s·m ⁻¹]	T_g	Greenhouse surface temperatures
l	Characteristic dimension of the leaf surface	T_r	Greenhouse cover or screen temperature
L_d	Long wave radiation exchanges at the lower leaf surfaces	T_{c0}	Crop temperature at crop level leaf area index of 0
L_n	Long-wave radiation exchange between the leaves and the greenhouse	τ_d	Penetration functions for downward long-wave radiation
L_u	Long-wave radiation exchanges at the upper leaf surfaces	τ_u	Penetration functions for upward long-wave radiation
$L_d(0)$	Radiation exchanges from lower leaf surfaces at a crop level leaf area index of 0	θ	Atmospheric pressure
$L_u(0)$	Radiation exchanges from upper leaf surfaces at a crop level leaf area index of 0	u	Air velocity
LAI	Leaf area index	VPD_s	Vapor pressure deficit at the leaf surface
λE	Latent heat of evaporation	ν	Kinematic viscosity of air
Nu	Nusselt number	χ	Thermal diffusivity of air
		$z (z_1, z_2, z_3)$	Vertical leaf layer (top, middle, bottom)