

Modeling Shoot-tip Temperature in the Greenhouse Environment

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ABSTRACT. An energy-balance model is described that predicts *vinca* (*Catharanthus roseus* L.) shoot-tip temperature using four environmental measurements: solar radiation and dry bulb, wet bulb, and glazing material temperature. The time and magnitude of the differences between shoot-tip and air temperature were determined in greenhouses maintained at air temperatures of 15, 20, 25, 30, or 35 °C. At night, shoot-tip temperature was always below air temperature. Shoot-tip temperature decreased from 0.5 to 5 °C below air temperature as greenhouse glass temperature decreased from 2 to 15 °C below air temperature. During the photoperiod under low vapor-pressure deficit (VPD) and low air temperature, shoot-tip temperature increased ≈ 4 °C as solar radiation increased from 0 to 600 W·m⁻². Under high VPD and high air temperature, shoot-tip temperature initially decreased 1 to 2 °C at sunrise, then increased later in the morning as solar radiation increased. The model predicted shoot-tip temperatures within ± 1 °C of 81% of the observed 1-hour average shoot-tip temperatures. The model was used to simulate shoot-tip temperatures under different VPD, solar radiation, and air temperatures. Since the rate of leaf and flower development are influenced by the temperature of the meristematic tissues, a model of shoot-tip temperature will be a valuable tool to predict plant development in greenhouses and to control the greenhouse environment based on a plant temperature setpoint.

Commercial production of greenhouse crops requires precise control of plant development so that plants can be grown to buyer size and date specifications. Meristematic tissue temperature, e.g., the shoot tip, is a primary factor controlling the rate of plant development (Harris and Scott, 1969; Ritchie and NeSmith, 1991; Watts, 1972). Growers adjust air temperature to control plant development; however, accurate timing of a crop can be jeopardized when plant shoot temperature differs from air temperature. A knowledge of the relationship between shoot-tip and air temperature improves the ability to precisely time crop development to meet date specifications (Faust and Heins, 1993) and provides the opportunity to control the greenhouse environment based on a plant temperature setting, not air temperature.

Crop development models typically use minimum and maximum air temperature or mean air temperature data. Use of more frequent measurement, i.e., average hourly temperatures, does not necessarily improve crop development predictions (Faust and Heins, 1993). Average day and night air temperatures have been used for a poinsettia stem elongation model (Berghage, 1989; Karlsson and Heins, 1994). More frequent temperature measurements are required for greenhouse climate control; therefore, a plant temperature model used for climate control must be able to track plant temperatures accurately over time. We believe that model prediction can be improved by identifying the difference between the mean 24-h plant and air temperatures.

The physical processes involved in energy transfer between plants and the surrounding environment have been clearly described (Gates and Papian, 1971; Mellor et al., 1964; Raschke 1960). Most plant energy balance models were developed for leaves (Gates and Papian, 1971; Stanghellini, 1987), since leaf temperatures influence transpiration and photosynthesis and, thus,

growth and yield. However, for ornamental potted plant production, shoot-tip temperature is a more valuable measurement, since the timing of plant development has a greater economic impact than that of fresh or dry mass.

Energy transfer is a complex process, and models developed to describe energy transfer in greenhouses are complex (Kimball, 1973; Kindelan, 1980; Levit and Gaspar, 1988). Mechanistic models often contain many variables that are difficult to quantify and difficult to adapt to different greenhouse situations. Functional models contain fewer variables that use environmental measurements and are more easily adapted to different locations (Ritchie and Johnson, 1990). The lack of uniformity among greenhouse structures and plant species indicates that the model must be robust and adaptable for it to become of practical use in research and commercial greenhouses.

The first objective of this project was to identify the conditions under which shoot-tip temperature differed from air temperature. Second, we aimed to develop an accurate model of shoot-tip temperature that used environmental inputs that could be measured in commercial greenhouses and could be adapted for use in different greenhouses and with different crops.

Materials and Methods

GENERAL PROCEDURE. *Vinca* (*Catharanthus roseus*) plants were grown in 48-cell packs in five 10-m² greenhouses set to maintain air temperatures at 15, 20, 25, 30, or 35 °C. Plants were ≈ 10 cm tall at the start of the experiment. Fine-wire (80 μ m-diameter) chromel-constantan thermocouples were inserted in the shoot tip of four plants in each greenhouse. Thermocouples were re-inserted every 2 to 3 d as shoots elongated. Other thermocouples were placed in contact with the inside of the greenhouse glass to calculate longwave radiation (3,000 to 50,000 nm) emitted from the greenhouse structure. The precision of the thermocouples was about ± 0.15 °C. Pyranometers (LI-200SA; LI-COR, Lincoln, Nebr.) were mounted 10 cm below the greenhouse glass and also at canopy height to measure shortwave radiation (300 to 3,000 nm) transmitted to the plant canopy. Wet and dry bulb measurements were made with thermistors placed inside a shaded, aspirated weather station

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Table 1. Definitions of symbols, units, and default values for parameters in the shoot-tip temperature model described in Eqs. [1–11]. These values will vary with species, greenhouse, elevation, etc.

Symbol	Definition	Unit	Value
Longwave radiation properties			
e_{shoot}	Shoot emissivity	Dimensionless	0.96
a	Stephan-Boltzmann constant	5.67×10^{-8}	
VF	Viewfactor	Dimensionless	0.60
LW_{net}	Net longwave radiation	$W \cdot m^{-2}$	
Shortwave radiation properties			
SW_{abs}	Shortwave radiation absorbed	$W \cdot m^{-2}$	
t_{sw}	Short wave transmissivity (through greenhouse structure)	Dimensionless	0.65
a_{sw}	Shortwave absorptivity (by shoot)	Dimensionless	0.50
$PPF_{W \cdot m^{-2}}$	PPF/ $W \cdot m^{-2}$ Shortwave radiation	$mmol \cdot m^{-2} \cdot s^{-1} / W \cdot m^{-2}$	2.0
Convective heat transfer property			
h_c	Heat transfer coefficient	$W \cdot m^{-2} / ^\circ C$	15
Transpiration properties			
g_{wv}	Water vapor conductance	$mmol \cdot m^{-2} \cdot s^{-1}$	
VP ^{shoot}	Shoot vapor pressure	kPa	
VP ^{air}	Air vapor pressure	kPa	
VP _{wb}	Wet bulb vapor pressure	kPa	
P_a	Atmospheric pressure	kPa	95
Measured parameters			
T_{air}	Air temperature	$^\circ C$	
T_{wb}	Wet bulb temperature	$^\circ C$	
T_{glass}	Glass temperature	$^\circ C$	
SW_{glass}	Shortwave radiation (measured below the glass)	$W \cdot m^{-2}$	
Predicted parameter			
T_{shoot}	Shoot-tip temperature	$^\circ C$	

located at canopy height. A datalogger (CR10; Campbell Scientific Inc., Logan, Utah) recorded environmental data from the various sensors from 13 to 31 May 1993 for the model development experiment.

Greenhouse air temperatures were maintained with an environmental-control computer (PRIVA; De Lier, The Netherlands). Heat was delivered with steam-heating units located along the base of the greenhouse walls below bench level. Cooling was controlled with ridge vents and a three-stage forced air cooling system consisting of a low-speed fan, high-speed fan, and a high-speed fan combined with evaporative pads. The greenhouses did not contain horizontal air-flow fans or an infrared heat source above the canopy.

MODEL DEVELOPMENT. Under steady-state conditions, plant temperature maintains a definable relationship with the surrounding environment. The energy gain of the plant equals the energy loss; thus, the sum of the energy transfer [i.e., radiation, convection, and transpiration (latent heat of vaporization)], is zero (Eq. [1]).

$$\text{Radiation} + \text{convection} + \text{transpiration} = 0 \quad [1]$$

Steady state was assumed, since vinca has a relatively thin stem and, thus, a short response time to come to thermoequilibrium relative to the 30-min data collection interval.

The energy transfer components are described with the following equations:

$$\text{Radiation} = SW_{\text{abs}} + LW_{\text{net}} \quad [2]$$

$$SW_{\text{abs}} = SW_{\text{glass}} \times t_{\text{sw}} \times a_{\text{sw}} \quad [3]$$

$$LW_{\text{net}} = VF \times e_{\text{shoot}} \times a \left((T_{\text{glass}} + 273.15)^4 - (T_{\text{shoot}} + 273.15)^4 \right) \quad [4]$$

$$\text{Convection} = h_c (T_{\text{air}} - T_{\text{shoot}}) \quad [5]$$

$$\text{Transpiration} = -g_{\text{wv}} (VP_{\text{shoot}} - VP_{\text{air}}) / P_a \quad [6]$$

$$g_{\text{wv}} = (b_0 - b_1 \exp(-b_2 \text{PPF})) / 44 \text{ J} \cdot \text{mmol}^{-1} \quad [7]$$

$$\text{PPF} = \text{PPF}_{W \cdot m^{-2}} \times SW_{\text{Glass}} \times t_{\text{sw}} \quad [8]$$

$$VP_{\text{shoot}} = \exp(19.0177 - (5327/T_{\text{shoot}} + 273.15)) \quad [9]$$

$$VP_{\text{wb}} = \exp(19.0177 - (5327/T_{\text{wb}} + 273.15)) \quad [10]$$

$$VP_{\text{air}} = VP_{\text{wb}} - 0.00066(1 + 0.00115 T_{\text{wb}})(T_{\text{air}} - T_{\text{wb}}) P_a \quad [11]$$

Definitions of symbols, units, and default values are listed in Table 1. Parameter estimates for Eq. [7] are listed in Table 2.

A computer program was written and compiled in Turbo Pascal (Borland International, Scotts Valley, Calif.) to use Eqs. [1–11] to find a value for T_{shoot} . The computer code used a mathematical recipe (Press, 1989) that used the root bisection technique to find a solution for Eq. [1].

Measurements of shortwave radiation below the glass and at canopy height indicated that $\approx 65\%$ was transmitted to the canopy (i.e., $t_{\text{sw}} = 0.65$). According to Nobel (1991), $\approx 50\%$ of the incident

Table 2. Parameter estimates for Eq. [7] ($r^2 = 0.744$).

Parameter	Estimate	Asymptotic SE	Asymptotic 95% confidence interval	
			Lower	Upper
b_0	167.3	1.94	163.5	171.1
b_1	134.2	2.48	129.4	139.1
b_2	0.0121	0.000856	0.0104	0.0137

solar shortwave radiation is absorbed by plants (i.e., $a_{sw}=0.50$). No distinctions were made between direct and diffuse shortwave radiation.

To estimate longwave radiation exchange, we assumed that there was no net longwave radiation exchange between the shoot tip and the surrounding foliage below the horizontal plane through the shoot tip. A view factor (VF) term was used to estimate the percentage of the hemisphere above the horizontal plane that was occupied by glass exposed to the outside environment. We calculated that 60% of the surrounding greenhouse structure was exposed to outside temperatures, while the other 40% was occupied by relatively warm side walls (i.e., $VF=0.60$). The emissivity term (e_{shoot}) estimates the plants' emissivity and absorptivity of longwave radiation. A value of 0.96 is used for e_{shoot} (Nobel, 1991).

Conductance of water vapor from the plant to the greenhouse air (g_{wv}) can be defined as the sum of individual conductances (i.e., stomatal, cuticular, boundary layer, and intercellular layer). However, to maintain simplicity in the models, only the total conductance was considered. Values for conductance were calculated using the measured plant temperatures and the measured environmental variables in the model development experiment to solve the energy balance equations (Eqs. [1–11]) for conductance. An exponential function was used to describe conductance as a function of PPF (Eq. [7]). Parameter estimates for Eq. [7] are shown in Table 2.

VALIDATION. The accuracy of the vinca shoot-tip temperature model was measured with data collected on vinca plants grown in a 10-m² greenhouse. The plants were grown for 12 d at air temperatures of 15, 25, or 35 °C from 21 Oct. to 4 Nov. 1993.

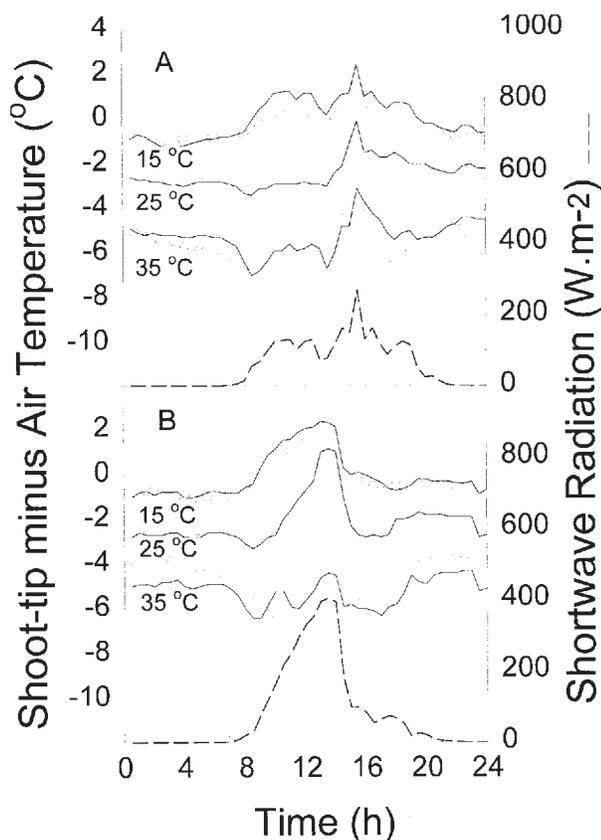


Fig. 1. Predicted (solid lines) and observed (symbols) difference between vinca shoot-tip and air temperatures recorded in the 15 °C (○), 25 °C (□), and 35 °C (Δ) greenhouses on (A) a cloudy day (27 May 1993) and (B) a partly sunny day (30 May 1993). The dashed line indicates the shortwave radiation in W·m⁻².

Environmental measurement and data recording were performed in the same fashion as in the model-development experiment.

SIMULATION. Environmental data were entered into the model to examine the possible deviations between average daily shoot-tip temperatures observed on plants grown at air temperatures of 15, 20, 25, 30, or 35 °C and average daily VPD of 0.4, 0.8, 1.6, or 2.4 kPa on four types of days: sunny and cold, sunny and warm, cloudy and cold, and cloudy and warm. Polynomials were developed to estimate the glass temperature as a function of greenhouse air temperature and shortwave radiation measured below the glass on days when outside air temperature was between 0 and -10 °C (cold) [$T_{Glass} = -1.36 + 1.101T_{air} - 0.014T_{air}^2 + 0.0301SW_{Glass}$] or between 10 and 20 °C (warm) [$T_{Glass} = -6.0 + 0.73T_{air} - 0.005T_{air}^2 + 0.025SW_{Glass}$]. The maximum solar radiation incident on the crop canopy was 470 W·m⁻² for the simulation of sunny days, while on the simulated cloudy day solar radiation never exceeded 120 W·m⁻². The daily integrated PPF for the sunny and cloudy days was 24 and 6 mol·m⁻²·d⁻¹, respectively.

SENSITIVITY ANALYSIS. To assess the effects of model parameters (VF, h_c , g_{wv}) on shoot-tip temperature prediction, a shoot-tip temperature prediction was made for a hypothetical day during which the maximum solar radiation was 470 W·m⁻², the glass temperature ranged from 10 °C at night to 24 °C during the day, and air temperature was maintained at 20 °C. Individual parameter estimates were manipulated to observe the effect of the specific parameter on model prediction. Values were 5 and 25 for h_c , 0.3 and 0.9 for VF, 0.005 and 0.015 for b_2 , and 120 and 220 for b_0 . The b_2 term in Eq. [7] influenced the rate of increase in conductance with respect to PPF. The b_0 term in Eq. [7] represents the maximum conductance, i.e., the asymptote. The b_1 term was changed to the same magnitude as the b_0 term so that the intercept, or dark conductance, would not be affected.

Results

SHOOT-TIP TEMPERATURES. Vinca shoot-tip temperature was seldom the same as the greenhouse air temperature (Fig. 1). The temperature of the plants grown in the 15 °C greenhouses was equal to air temperature only for a brief period during the morning and late afternoon, while the temperature of the plants grown in the 35 °C greenhouses was nearly always below air temperature.

At night, shoot-tip temperature was always below air temperature. Shoot-tip night temperature decreased relative to air temperature as glass temperature decreased relative to air temperature (Fig. 2). Shoot-tip temperature was as much as 5 °C below air temperature when the glazing material temperature was 16 °C below air temperature. Most of the observed shoot-tip night temperature depression was attributable to the loss of longwave radiation to the glazing material; however, since the model estimates that dark conductance occurred at 33 mmol·m⁻²·s⁻¹, a VPD value >0 will result in evaporative cooling during the night (Eq. [6]).

Shoot-tip temperature during the photoperiod was influenced by shortwave radiation and VPD (Fig. 3). Under the relatively low VPD conditions (0.44 kPa) in the 15 °C greenhouse, shoot-tip temperature increased as the incident solar radiation increased (Fig. 3A). Under relatively high VPD conditions (1.76 kPa) in the 35 °C greenhouse, shoot-tip temperature decreased as the incident shortwave radiation increased from 0 to ≈100 W·m⁻², then increased as the incident shortwave radiation increased above 100 W·m⁻² (Fig. 3E). The shortwave radiation at which shoot-tip temperature began to increase relative to air temperature increased as VPD and air temperature increased.

The 24-h average shoot-tip temperature decreased with respect

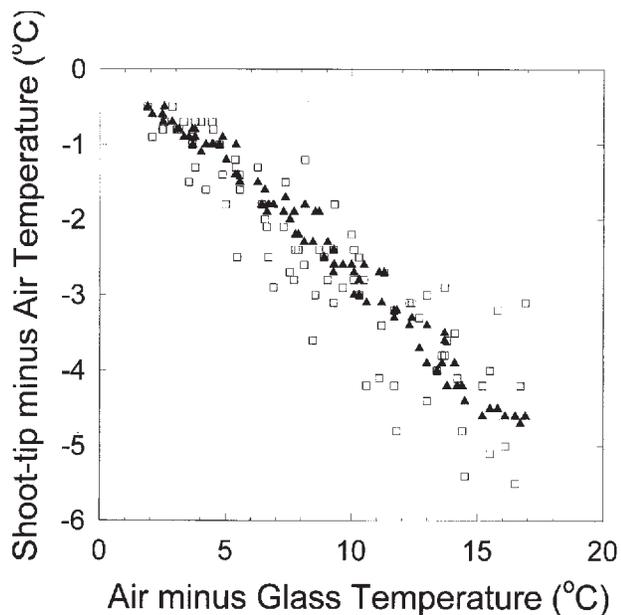


Fig. 2. Predicted (▲) and observed (□) difference between vinca shoot-tip temperature and air temperature as influenced by longwave radiation exchange between the canopy and the glazing material. Data are shown as the difference between air and glass temperature.

to air temperature as air temperature increased. In the 15 and 20 °C greenhouses, the 24-h average shoot-tip temperature was typically within 2 °C of the air temperature, while in the 35 °C greenhouse the average daily shoot-tip temperature was typically 4 to 6 °C below air temperature. Night shoot-tip temperatures were lower than the day shoot-tip temperatures at equivalent air temperatures. The scatter of air temperature data was greater during the day in the 15 and 20 °C greenhouses because of the loss of air temperature control on warm and sunny days. Plants grown at day temperatures <25 °C were within ± 2 °C of air temperature during the day, while plants grown at day temperatures >25 °C were always below air temperature during the day. Shoot-tip night temperatures were always below air temperatures.

MODEL PREDICTION. The vinca shoot-tip temperature model accurately described the shoot-tip temperature throughout a 24-h period on a cloudy (Fig. 1A) and a sunny (Fig. 1B) day. Eighty-one percent of the model 1-h predictions were within ± 1 °C of the measured temperature, while 88% of the model 24-h predictions were within ± 1 °C of the measured temperatures.

VALIDATION. Fifty percent of the predicted temperatures were within ± 1 °C of the measured temperatures in the validation experiment. Plants in this experiment were grown on a bench located within 50 cm of a greenhouse side wall that divided two greenhouses, so the VF was estimated to be 0.30. Also, the asymptote of the conductance function was lowered to $120 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ to reduce the transpiration estimated during the photoperiod. After these two adjustments were made, 83% of the predicted temperatures were within ± 1 °C of the measured temperatures.

SIMULATION. The simulated 24-h average shoot-tip temperatures were nearly always below air temperature (Fig. 4). Only when conditions were sunny and warm (the greenhouse air temperature was ≤ 20 °C and the VPD was ≤ 0.8 kPa) did the simulated 24-h average shoot-tip temperature exceed air temperature (Fig. 4B). The simulated 24-h average shoot-tip temperature was 0.4 to 1.9 °C higher on sunny days than cloudy days and 1.0 to 1.3 °C higher on warm days than cold days. The largest temperature difference (1.6 to 3.1 °C) occurred between sunny and warm

versus cloudy and cold days. The simulated 24-h average shoot-tip temperature decreased 4 to 5 °C as VPD increased from 0.4 to 2.4 kPa. In the 15 and 20 °C air temperature environments, VPD had a smaller effect on 24-h shoot-tip temperature since the possible range of VPD was relatively small.

SENSITIVITY ANALYSIS. Varying the convective heat transfer coefficient (h_c) had a greater impact on night temperatures than day temperatures (Fig. 5 A and B). Lowering the value of h_c from 15 to 5 resulted in a larger difference between shoot-tip and air temperature. Increasing the value of h_c from 15 to 25 increased the convective heat transfer between the plant and the greenhouse air, resulting in shoot-tip temperatures closer to air temperature.

VF influences longwave radiation incident on the shoot-tip. Increasing VF lowered shoot-tip temperature when the glass was colder than the plant, i.e., during low solar radiation, and increased plant temperature when the glass was warmer than the plant, i.e., during high solar radiation (Fig. 5 C and D). The reverse occurred when VF decreased.

The b_2 parameter in Eq. [7] affected shoot-tip temperature when the PPF incident on the canopy was relatively low, i.e., immediately after sunrise and before sunset (Fig. 5 E and F). This parameter represents the rate of conductance increase or decrease, which is primarily influenced by stomatal opening and closing; thus, the b_2 parameter affected shoot-tip temperatures immediately after sunrise and before sunset. Increasing b_2 increased transpiration and, thus, reduces plant temperature, while decreasing b_2

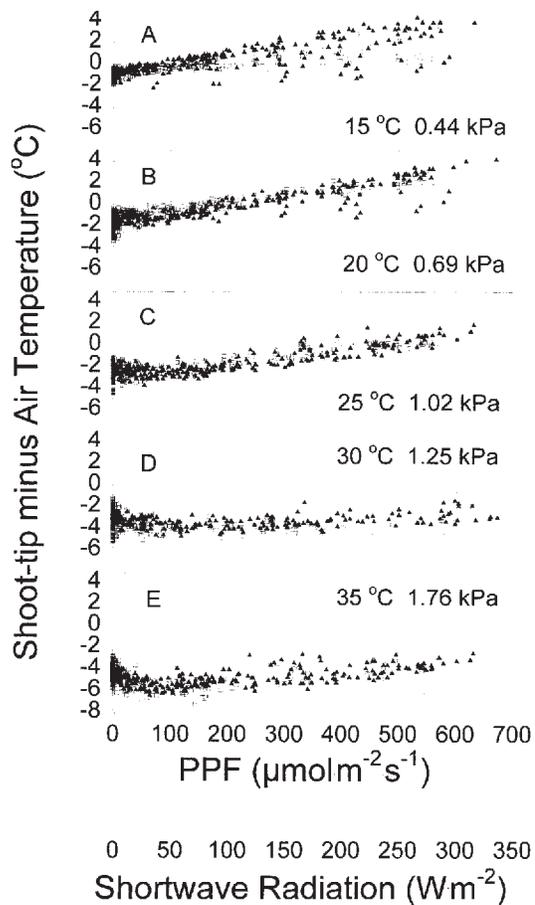


Fig. 3. Predicted (▲) and observed (□) difference between vinca shoot-tip temperature and air temperatures observed in (A) 15, (B) 20, (C) 25, (D) 30, or (E) 35 °C greenhouse, shown as a function of photosynthetic photon flux density (PPF) incident on the canopy. Vapor pressure deficits were 0.44, 0.69, 1.02, 1.75, and 1.76 kPa at 15, 20, 25, 30, and 35 °C, respectively.

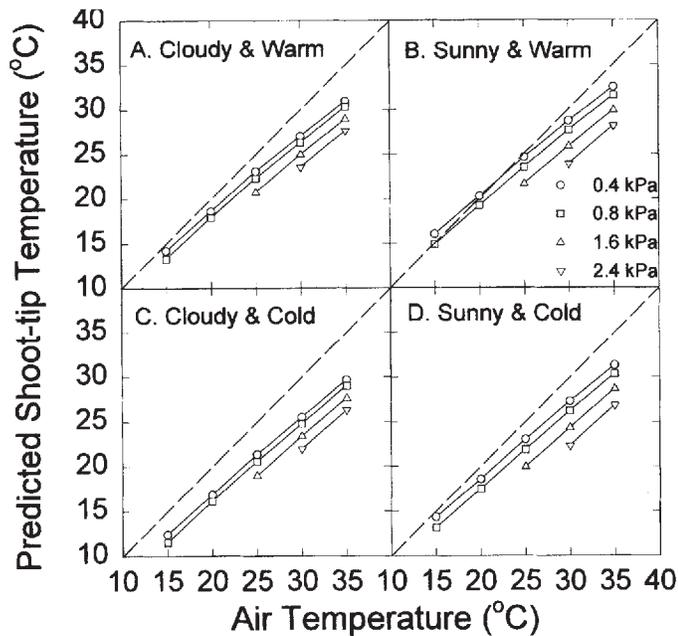


Fig. 4. A simulation of 24-h average vinca shoot-tip temperatures in four vapor-pressure deficits in each of four types of weather conditions: (A) cloudy and warm, (B) sunny and warm, (C) cloudy and cold, or (D) sunny and cold. Cold and warm days were defined as outside air from -10 to 0 °C and 10 to 20 °C, respectively. Cloudy and sunny days were defined as the shortwave radiation maximum at 120 and 470 $W \cdot m^{-2}$, respectively.

results in an increase in plant temperature.

Maximum conductance of water vapor, the b_0 parameter in Eq. [7], influenced potential transpiration. Decreasing b_0 resulted in warmer shoot-tip temperatures during the day (Fig. 5G), while increasing this parameter resulted in cooler day temperatures (Fig. 5H). Assuming the y-intercept (calculated as b_0 minus b_1) in Eq. [7] is held constant, neither b_0 nor b_2 affects shoot-tip temperatures during the night.

Discussion

Energy transfer processes, i.e., convection, transpiration, and radiation, are interdependent, and the energy balance calculations allow us to determine the relative importance of each process during the day and night. During the night, the exchange of longwave radiation from the plant canopy to the glazing material is the primary factor influencing plant and air temperature. We observed shoot-tip temperatures 5 °C lower than air temperature when the glass temperature was 16 °C below air temperature. The magnitude of the shoot-tip temperature depression is limited by convective heat transfer. Convection acts to couple air and plant temperature, so that the higher the heat transfer coefficient, the smaller the shoot-tip temperature depression. Shoot-tip temperature depression at night can also be a result of transpiration. Faust and Heins (1997) reported a 1.3 °C decrease in vinca shoot-tip temperature as VPD increased from 0.5 to 3.0 kPa. The estimated dark conductance for vinca was 33 $mmol \cdot m^{-2} \cdot s^{-1}$, which is similar to the dark stomatal conductance for greenhouse cucumber leaves (Yang et al., 1990).

A method of reducing the shoot-tip night temperature drop is to increase convective heat transfer by using horizontal air-flow fans to increase the air velocity surrounding the canopy. Air velocity was not a required measurement in the proposed shoot-tip model. Horizontal air-flow fans are often used to provide a constant low

air velocity, while high-volume fans are used for large-volume air exchange with the outside environment. Therefore, air velocity in commercial greenhouses is relatively constant until high-volume fans are used. Consequently, errors in prediction are likely to occur when high-volume fans are used. We chose not to include air velocity in our model, since greenhouse air velocities are generally low, i.e., <20 $cm \cdot s^{-1}$, and growers do not typically measure air velocity because expensive and fragile hot-wire anemometers would be required for accurate measurements. Air velocity could be added to the model by using an equation that uses air velocity and a plant dimension term to calculate the heat-transfer coefficient (Rosenberg et al., 1983).

Shortwave radiation and transpiration result in the largest amount of energy transfer during the day, while the net longwave radiation and convection result in relatively small amounts of energy transfer. Solar radiation and VPD, therefore, have a strong impact on the difference between shoot-tip and air temperature during the photoperiod. Although, it was not possible to separate the effect of air temperature and VPD in this experiment (since VPD increased as air temperature increased), the model predictions suggest that changes in VPD explain much of the observed plant and air temperature differences.

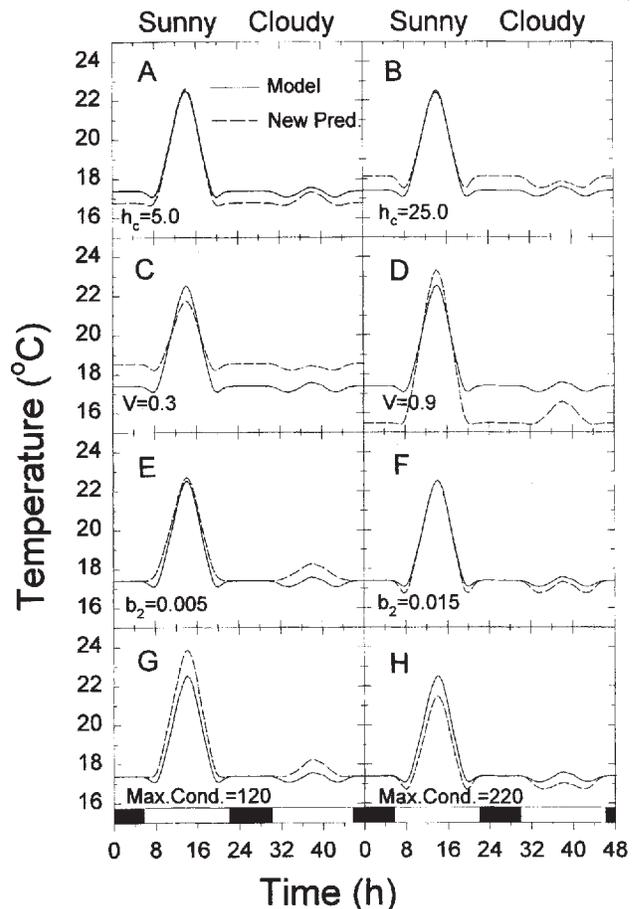


Fig. 5. Comparison of model prediction of shoot-tip temperature over a 2-d period and model prediction after (A and B) the heat transfer coefficient (h_c); (C and D) the viewfactor (VF); (E and F) the b_2 parameter in Eq. [7]; and (G and H) the maximum conductance perimeter (b_0) were individually altered as indicated. Weather data simulated greenhouse conditions on a sunny day followed by a cloudy day when greenhouse air was maintained at constant 20 °C. Sunny and cloudy days were defined as the shortwave radiation maximum at 470 and 120 $W \cdot m^{-2}$, respectively. The default value for h_c was 15 ; for VF, 0.6 ; for b_2 , 0.0121 ; and for b_0 , 167 .

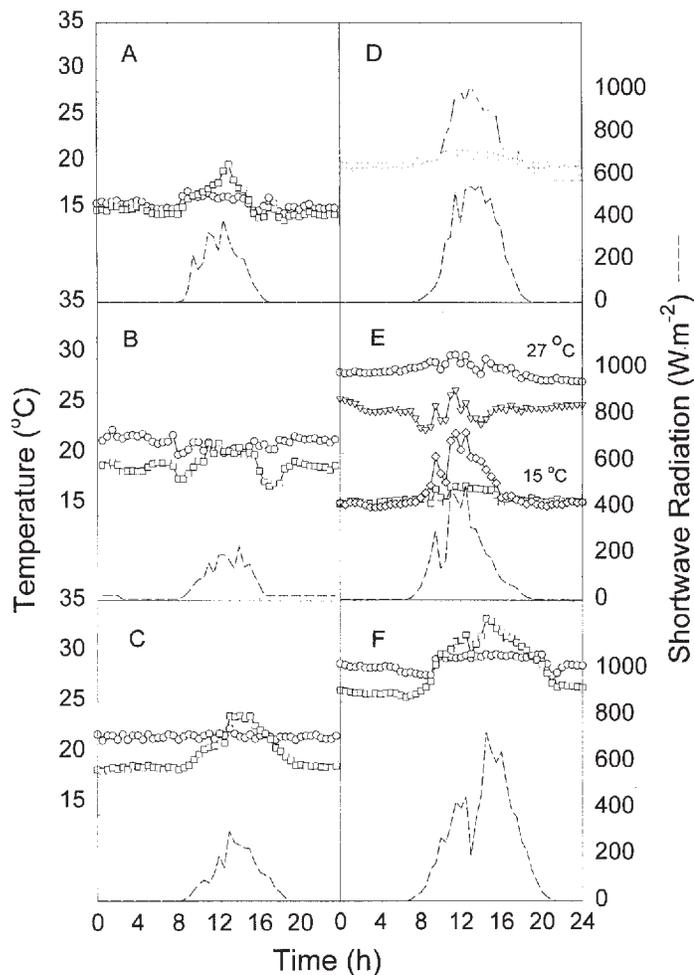


Fig. 6. Examples of plant and air temperatures measured on species grown in several greenhouses during different times of the year. The solid line indicates the shortwave radiation in $\text{W}\cdot\text{m}^{-2}$. (A) Poinsettia (*Euphorbia pulcherrima*) cyathia (◻) and air (○) temperatures Henry Mast's Greenhouses, Byron Center, Mich., 15 Dec. 1992 (thermal screens at night). (B) Geranium (*Pelargonium xhortorum*) shoot tip (◻) and air (○) temperatures at Raker's Acres, Litchfield, Mich., 25 Dec. 1993 (thermal screens at night, high-pressure sodium lamps from 1600 to 0200 HR.). (C) Begonia (*Begonia sempervirens*) shoot tip (◐) and air (○) temperatures at Snobelt Greenhouses, Kalamazoo, Mich., 17 Feb. 1993. (D) Easter lily (*Lilium longiflorum*) shoot tip (◻) and air (○) temperatures at Michigan State Univ. (MSU) research greenhouses, East Lansing, 2 Mar. 1993. (E) Oriental lily (*Lilium orientale* 'Stargazer') flower buds (◻) and air (○) temperatures at MSU research greenhouses 3 Apr. 1993. (F) Poinsettia (*Euphorbia pulcherrima*) axillary buds (◻) and air (○) temperatures at MSU research greenhouses 8 Aug. 1993.

Conductance was described as a function of PPF, not shortwave radiation, since stomatal opening and closing is influenced by visible radiation (400 to 700 nm), not the entire shortwave radiation spectrum. The model predicts a rapid increase in conductance as PPF increases, which is apparently due to increased stomatal conductance because of stomatal opening. Conductance asymptotically approached a maximum of $170 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at $250 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. This maximum could have been limited by stomatal or boundary layer conductance, or both. The maximum conductance estimated compares with the typical leaf conductance for crop species—80 to $400 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, reported by Nobel (1991).

The net longwave exchange between the plant and the glazing material during the day can be positive or negative. Glazing material temperature increases in direct proportion to solar radiation, so on sunny days the canopy may experience a net radiation gain, since the glazing material may be warmer than the plant

canopy. We have observed glazing materials at 38°C while greenhouse air temperature was 30°C and shortwave radiation was $500 \text{ W}\cdot\text{m}^{-2}$. Whitewash applied to the glazing material reduces shortwave loads during the summer and increases the reflectivity and absorptivity of the glazing. Since the model uses glazing temperature to estimate the longwave radiation incident on the canopy, shade cloth placed between the canopy and the glazing will cause an error in estimating longwave radiation.

Plant morphology certainly influences the energy transfer processes (Gates and Papian, 1971). Preliminary data collected on Oriental lily (*Lilium orientale* 'Stargazer') flower bud temperatures, Easter lily (*Lilium longiflorum*) shoot-tip, poinsettia (*Euphorbia pulcherrima*) cyathia, and begonia (*Begonia sempervirens*) shoot-tip temperatures indicate that most greenhouse-grown plants follow a temperature pattern similar to that of vinca; however, the magnitude of the temperature response may be different (Fig. 6). If necessary, a plant dimension term can be added to the model by using an equation that uses air velocity and a plant dimension term to calculate the heat-transfer coefficient (Rosenberg et al., 1983).

The model was kept relatively simple to make it more adaptable to different species and greenhouses. Longwave radiation, convection, and transpiration equations were set up in the form of a driving gradient multiplied by a conductance ($1/\text{resistance}$) term. Driving gradients were determined by environmental measurements. Conductance terms for longwave, convection, and transpiration (i.e., V_f , h_c , g_{wv}) provide a means to manipulate model prediction to accommodate different greenhouse structures and crops. A researcher should be able to adjust the parameters based on knowledge of a particular greenhouse or species. However, based on the observed variation among greenhouses and species, we believe actual shoot-tip temperature measurements are necessary to calibrate the model to a particular situation. Shoot-tip temperatures could be measured with small hand-held dataloggers placed in the greenhouse for several days, after which the measured and predicted temperatures could be compared. Figure 5 displays the effect different parameters have on prediction. These predictions suggest how parameters could be adjusted to match the predicted to the observed temperatures accurately. We envision a user-friendly software interface that would allow the grower to choose different parameter values and immediately view the change in prediction.

To predict plant temperatures, the model requires that a mini weather station measure air temperature, humidity, and shortwave and longwave radiation. Air temperature and humidity are commonly measured in commercial greenhouses with aspirated and shaded dry and wet bulb sensors. Many greenhouses have pyranometers, i.e., shortwave radiation sensors, that frequently are located outside the greenhouse. However, this location cannot account for shortwave radiation reduction caused by shade curtain systems or whitewash applied to the glazing material. Canopy-level sensors are prone to error caused by shadows cast by the greenhouse structure. We propose that a line quantum sensor be placed above the plant canopy to measure PPF. This sensor integrates PPF measurements $>1 \text{ m}$, which will minimize errors due to shadows. Conversion of PPF to shortwave depends on the radiation source (Thimijan and Heins, 1983), so supplemental lighting would cause some errors in calculating shortwave radiation. Longwave radiation measurements made with sensors attached to the greenhouse glazing material do not provide accurate data when shade cloth, thermal screens, or supplemental lighting is used. A better option would be an infrared sensor placed above the canopy and pointed toward the greenhouse glazing to measure the longwave radiation incident on the plant canopy.

In this paper we show that shoot-tip temperature can be predicted with a model using four environmental variables: solar radiation and dry bulb, wet bulb, and glazing material temperature. In all cases observed, the predicted plant temperature more accurately reflected the observed shoot-tip temperature than did air temperature. This model may be useful in developing a climate-control system that is based on a plant temperature setpoint, not air temperature.

Literature Cited

- Berghage, Jr., R.D. 1989. Modeling stem elongation in the poinsettia. PhD diss. Michigan State Univ., East Lansing.
- Faust, J.E. and R.D. Heins. 1993. Modeling leaf development of the African violet (*Saintpaulia ionantha* Wendl.). *J. Amer. Soc. Hort. Sci.* 118:747-751.
- Faust, J.E. and R.D. Heins. 1998. Quantifying the influence of high-pressure sodium lighting on shoot-tip temperature. *Acta Hort.* (In press.)
- Gates, D.M. and L.E. Papian. 1971. Atlas of energy budgets of plant leaves. Academic Press, New York.
- Harris, G.P. and M.A. Scott. 1969. Studies on the glasshouse carnation: Effects of light and temperature on the growth and development of the flower. *Ann. Bot.* 33:143-152.
- Karlsson, M.G. and R.D. Heins. 1994. A model of chrysanthemum stem elongation. *J. Amer. Soc. Hort. Sci.* 199:403-407.
- Kimball, B.A. 1973. Simulation of the energy balance of a greenhouse. *Agr. Meteorol.* 11:243-260.
- Kindelan, M. 1980. Dynamic modeling of greenhouse environment. *Trans. Amer. Soc. Agr. Eng.* 1232-1239.
- Levit, H.J. and R. Gaspar. 1988. Energy budget for greenhouses in humid-temperate climate. *Agr. For. Meteorol.* 42:241-254.
- Mellor, R.S., F.B. Salisbury, and K. Raschke. 1964. Leaf temperatures in controlled environments. *Planta* 61:56-72.
- Nobel, P. S. 1991. *Physicochemical and environmental plant physiology.* Academic Press, New York.
- Press, W. 1989. *Numerical recipes in Pascal: The art of scientific computing.* Cambridge Univ. Press, Cambridge, Mass.
- Raschke, K. 1960. Heat transfer between the plant and the environment. *Annu. Rev. Plant Physiol.* 11:111-126.
- Ritchie, J.T. and B.S. Johnson. 1990. Soil and plant factors affecting evaporation, p. 363-390. In: *Irrigation of agricultural crops.* Agronomy no. 30. Amer. Soc. Agron., Madison, Wis.
- Ritchie, J.T. and D.S. NeSmith. Temperature and crop development. 1991. In: J. Hanks and J.T. Ritchie (eds.). *Modeling plant and soil systems,* Agronomy No. 31. Amer. Soc. Agron, Madison, Wis.
- Rosenberg, N.J., B.L. Blad, and S.B. Verma. 1983. *Microclimate: The biological environment.* Wiley, New York.
- Stanghellini, C. 1987. Transpiration of greenhouse crops. PhD diss. Agricultural Univ., Wageningen, The Netherlands.
- Thimijan, R.W. and R.D. Heins. 1983. Photometric, radiometric, and quantum light units or measure: A review of procedures for interconversion. *HortScience* 18:818-821.
- Watts, W.R. 1972. Leaf extension in *Zea mays*. *J. Expt. Bot.* 23(76):713-721.
- Yang, X., T.H. Short, R.D. Fox, and W.L. Bauerle. 1990. Transpiration, leaf temperature and stomatal resistance of a greenhouse cucumber crop. *Agr. For. Meteorol.* 51:197-209.