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Dynamic modeling and simulation of greenhouse environments under several scenarios: A web-based application

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A B S T R A C T

Greenhouse crop production systems are located throughout the world within a wide range of climatic conditions. To achieve environmental conditions favorable for plant growth, greenhouses are designed with various components, structural shapes, and numerous types of glazing materials. They are operated differently according to each condition. To improve the pedagogy and the understanding of the complexity and dynamic behavior of greenhouse environments with different configurations, an interactive, dynamic greenhouse environment simulator was developed. The greenhouse environment model, based on energy and mass balance principles, was implemented in a web-based interactive application that allowed for the selection of the greenhouse design, weather conditions, and operational strategies. The greenhouse environment simulator was designed to be used as an educational tool for demonstrating the physics of greenhouse systems and environmental control principles. Several scenarios were simulated to demonstrate how a specific greenhouse design would respond environmentally for several climate conditions (four seasons of four geographical locations), and to demonstrate what systems would be required to achieve the desired environmental conditions. The greenhouse environment simulator produced realistic approximations of the dynamic behavior of greenhouse environments with different design configurations for 28-h simulation periods.

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1. Introduction

Greenhouse production systems were originally implemented in cold regions at northern latitudes in order to extend the production season of plants, where usually they will not grow optimally. However, current controlled environment agriculture (CEA) industries operate in different climate regions throughout the world, including semiarid and tropical regions. The spread of CEA industries located at diverse climate conditions has been driven by the increased demand for high quality and healthier products in a year-round fashion, by the availability of efficient transportation systems, by the increased development of greenhouse technologies, and by the accessibility of glazing and building materials. Proper design selection combined with these factors has made it feasible to economically implement greenhouse crop production systems in a variety of climates (Enoch and Enoch, 1999).

To overcome the less optimal climate conditions and to fulfill the specific environmental needs of various crops that supply market demand, greenhouse designs vary in structural shape, size, and glazing materials, and in the various types of equipment required to achieve the desired environmental conditions. The main environmental parameters controlled in a greenhouse include: (1) air temperature, (2) air moisture content, (3) aerial carbon dioxide (CO_2) concentration and (4) photosynthetic photon flux (PPF). Greenhouses are designed and equipped with exhaust fans, or ventilation openings that are large enough to provide outside air and maintain the inside atmosphere temperature, humidity and CO_2 concentration at the optimum levels. More efficient cooling methods, such as evaporative pads or fog systems may be provided in warmer climates to reduce the inside air temperatures, in colder climates, heating systems (hot air, root zone heating or hot water pipes) may be utilized, and CO_2 or light supplementation may be required (von Zabeltitz, 1999).

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The "optimum" environmental conditions have been heuristically determined and defined by growers and researchers through many years of experimentation, and today these optimum conditions are successfully achieved by implementing crop-specific blueprints for the manipulation of several actuators (exhaust fans, ventilation openings, shade curtains, heaters, boilers, water pumps, etc.) with simple ON–OFF control to reach desired set-points. However, with the advancements of computer technologies it has become possible to monitor and control several parameters, and to implement more sophisticated control strategies that are based on modern control theories. These control schemes depend on mathematical models, describing the dynamics of the coupled crop-greenhouse system, to adjust set-points dynamically to optimize crop growth for a given performance criterion (Seginer, 1993; van Straten et al., 2000).

As summarized by von Zabeltitz (1999) several greenhouse models, based on energy and mass balance equations, have been investigated in the past and they can be classified as static or dynamic models. The more complex models are coupled with the crop dynamics (e.g., Jones et al., 1988, 1990; Takakura et al., 1971), and they include several state variables describing the status of the system over time. Some models address specific phenomena, for example natural ventilation (e.g., Al-Helal, 1998; Boulard and Draoui, 1995; Boulard et al., 1999; Dayan et al., 2004; de Jong, 1990), forced ventilation (e.g., Arbel et al., 2003; Willits, 2003), evaporative cooling (e.g., Abdel-Ghany and Kozai, 2006; Baille et al., 1994; Boulard and Baille, 1993; Boulard and Wang, 2000), or heating systems (e.g., Bartzanas et al., 2005; Kempkes et al., 2000).

Newer research approaches for greenhouse climate control are based on an optimization principle, for example for reduced energy (e.g., Aaslyng et al., 2003; de Zwart, 1996; Körner, 2003), and water consumption (e.g., Blasco et al., 2007); for optimizing CO_2 usage (e.g., Jones et al., 1989; Linker et al., 1998; Seginer et al., 1986), or humidity control (e.g., Daskalov et al., 2006; Jolliet, 1994; Korner and Challa, 2003; Stanghellini, 1992). Other climate control schemes implement different type of control criteria such as economic-based optimal control (e.g., Tap, 2000; van Henten, 1994), adaptive control (e.g., Udink ten Cate, 1983), multi-objective hierarchical control (Ramirez-Arias, 2005), or nonlinear predictive control (e.g., El-Ghoumari, 2003). All these approaches offer the advantage of making efficient use of the resource in study, by maximizing the production return or minimizing the production cost, over the traditional greenhouse control strategies where the set-points are defined by the grower experience.

Greenhouse production systems have a complex dynamic driven by external factors (weather), control mechanisms (ventilation openings, exhaust fans, heaters, evaporative cooling systems, etc.), and internal factors (crop and internal components). Thus the more we understand the physics of the greenhouse environment, the better the greenhouse design and component selection that will improve the possibilities for success. Several efforts have been completed to increase the understanding of greenhouse crop production systems through the development of educational materials available on the Internet. Some of these efforts allow for access to interactive digital media describing most of the U.S. greenhouse industry (Tignor et al., 2005, 2006, 2007), to living laboratories through web-based monitoring systems that enhanced an asynchronous education by allowing students to monitor current and historical conditions of experimental greenhouse crops at different off-campus locations including one at the South Pole (Fitz-Rodriguez et al., 2003), to virtual labs with emphasis on control theory applied to greenhouse climate control (Guzmán et al., 2005b), or to a scale-down greenhouse model for remote test control strategies (Guzmán et al., 2005a). While the latter two interactive tools allow for remote access and control, they are tied to one specific greenhouse configuration design.

Several sophisticated and more complete greenhouse environment models currently exist, however they are too complicated to be implemented into a generic model to predict the behavior of a wide range of greenhouse designs and climate conditions. The current simplified greenhouse environment model, based on energy and mass balance equations follows the models proposed by Takakura (1976), and Takakura and Fang (2002).

The objective of the current project was to investigate and implement a dynamic greenhouse environment model describing the dynamic behavior of the greenhouse environment (inside global radiation, air temperature, and air moisture content) during a 28-h interval, which was applicable to different, user-selectable greenhouse design configurations and geographic locations, yet simple enough to be implemented in a web-based interactive application for educational purposes. The greenhouse environment dynamics is a complex phenomenon. It is not the objective of the current research to fully develop a model for detail and accuracy, but to simulate realistic environmental responses for educational purposes by demonstrating the fundamental dynamics of the greenhouse environment.

2. Materials and methods

This project was developed as part of a multi-institutional (The University of Vermont, University of Florida, The Ohio State University, and The University of Arizona) collaborative effort to develop web-based educational materials for worldwide greenhouse education (http://www.uvm.edu/wge/). The project included the development of: (1) digital videos describing the greenhouse production systems at each location, (2) a searchable repository of greenhouse educational materials including images, videos and software, (3) a web-based student evaluation method to determine the extent of learned greenhouse concepts, and (4) a greenhouse environment simulator (Tignor et al., 2006, 2007). The greenhouse environment simulator is a computer simulation program based on a greenhouse environment mathematical model and was programmed in ActionScript 2.0, and integrated into an interactive interface developed in Flash MX (Flash MX Pro 2004, Macromedia, San Francisco) (Fitz-Rodriguez, 2006). The components of the simulation program included climate data, a database of the greenhouse structure and hardware equipment features, and the mathematical model representing the physics of the greenhouse and crop environment.

2.1. Climate data

Climate data from the geographic locations representing each of the four universities were used to provide the outside environmental conditions as inputs to the simulations. Summarized by von Zabeltitz (1999) the two climate parameters defining the climate control strategies and crop production cycles are average daily insolation, and average daily air temperature. These are documented for the four sites in Fig. 1. Although in all four locations the limit of daily radiation (7.4 mol m^{-2} d^{-1}) (3.6 MJ m^{-2} d^{-1}) for effective production is exceeded, only Arizona and Florida have daily radiations above the minimum required for feasible winter production (17.1 mol m^{-2} d^{-1}). Vermont and Ohio will require artificial lighting for winter production. The daily average air temperature (T_{out24}) defines the type of climate control required. In this way, for the months of April through October when average air temperature is between 12 and 22 °C natural ventilation is enough to control the greenhouse environment for Vermont and Ohio. For any other month when $T_{out24} < 12$ °C a heating system is required. In contrast, the average air temperatures in Florida are above the threshold value ($T_{out24} > 22$ °C) defined as the need for an artificial

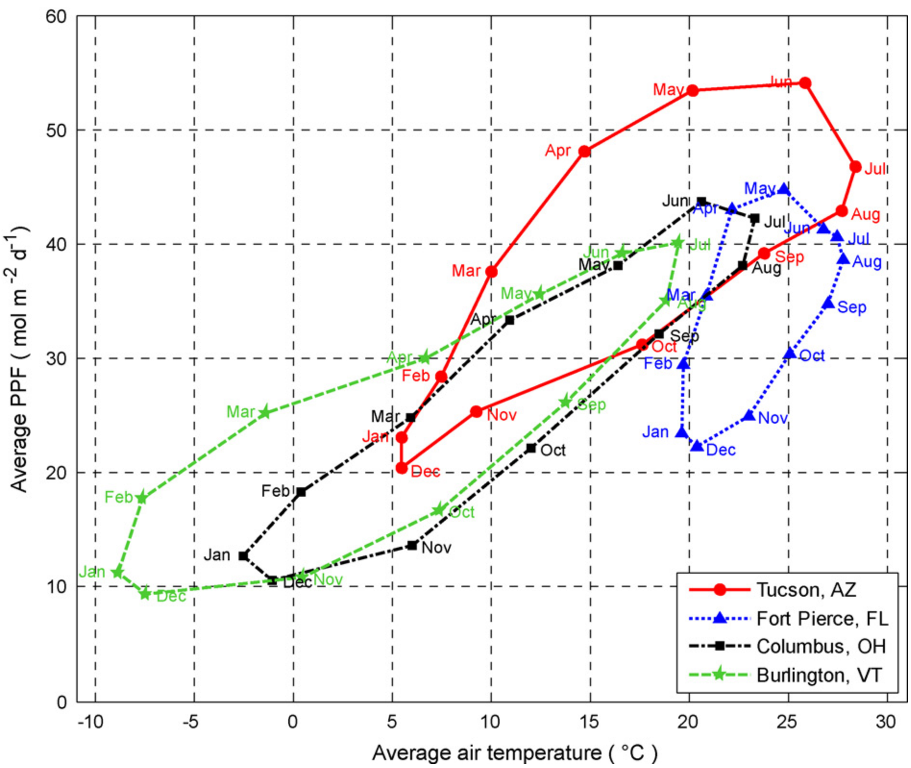

Fig. 1. Average photosynthetic photon flux (PPF) versus average daily air temperature for every month of the year for each location. Data source from NASA Surface Meteorology and Solar Energy: SolarSizer Data (http://eosweb.larc.nasa.gov/).

cooling system for most of the year. Arizona has the three situations, during the winter it requires heating, climate control only with natural ventilation is possible for several months, and during the summer an artificial cooling system is required. All four sites provided a wide range of possibilities to simulate the greenhouse environment during several production seasons.

2.2. Greenhouse structure and components

Greenhouse structures are designed to overcome the adversities of external (wind, rain, snow, etc.) environmental factors, and internal (live and dead) loads, while maximizing the solar radiation available for the crop. The greenhouse structural components and their geometry directly affect solar radiation transmission. The shape and size of the three greenhouse structural designs (Fig. 2) used in the simulations include: (1) A-frame, (2) Arch-roof and (3) Quonset style, that are some of the most widely used in small production systems. The geometry of the greenhouse designs implemented in the simulations is indicated in Table 1. The length of each was assumed as 30 m, while the widths were 10, 10 and 8, respectively.

The glazing material used in the simulations included single layer (glass, polyethylene film, and polycarbonate) and double layer (polyethylene film and polycarbonate) glazing. Their material properties are summarized in Table 2. Internal shade curtains were optional in the simulator and included effective shading values of 30, 50, and 70% reduction of outside solar radiation in addition to the reduction caused by the glazing material.

Although there are many types and sizes of heating systems in greenhouses such as steam, hot water, hot air and infrared radiation, only a hot air system was selectable. Heaters, with a capacity of 75 kW each, could be included in the simulation with 1 or 2 or none as possibilities.

The reduced air movement and air exchange within the greenhouse, imposed by the glazing material, results in a greater air temperature than outside. The greenhouse air temperature could be reduced with either natural or forced ventilation as selected by the user. Ventilation is a highly complex phenomenon and it was not the objective of the current research to rigorously model it. It was assumed that each simulated greenhouse environment had a ventilation rate equivalent to 2, 10, 20, 30, 60 and 120 air changes per hour ($AC\,h^{-1}$). The ventilation rates for each greenhouse design are slightly different, because of the differences in greenhouse volumes. Corresponding values are shown in Table 3.

Table 1
Dimensions and properties of greenhouse designs used in the simulations.

Property	A-frame	Arch-roof	Quonset
Length (m)	30	30	30
Width (m)	10	10	8
Gutter high (m)	4	4	–
Ridge high (m)	6.3	6.3	4
A_{fl} (m^2)	300	300	240
A_{gl} (m^2)	674	692	427
Volume (m^3)	1546	1677	745
w ratio (A_{gl}/A_{fl})	2.2	2.3	1.8

Table 2
Properties of the greenhouse glazing materials used in the simulations.

Layers	Greenhouse glazing	k-Value[a] ($W\,m^{-2}\,{}^{\circ}C^{-1}$)	Light transmissivity[b] (%)
Single	Glass	6.2	90
	Polyethylene	6.2	87
	Polycarbonate	6.2	87
Double	Polyethylene	4.0	76
	Polycarbonate	3.3	79

[a] Taken from ASAE (2003).
[b] Taken from Hanan (1998).

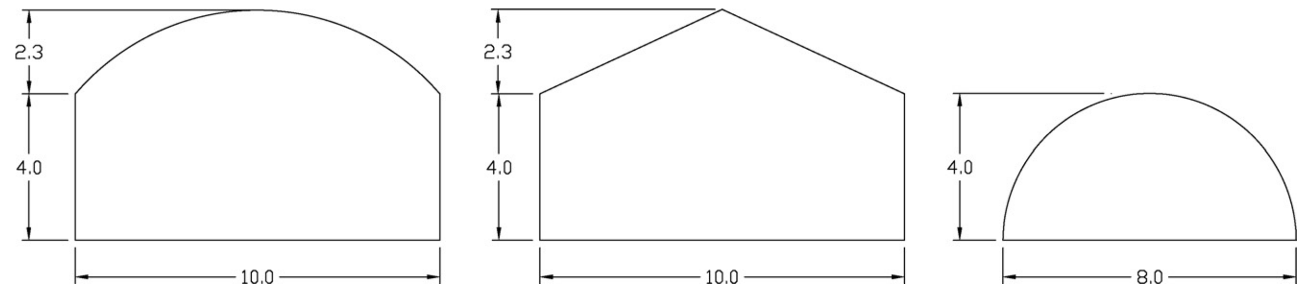

Fig. 2. Structural designs implemented in the greenhouse environment simulator. All three designs have 30 m of length, and are singlespan. Units are in meters.

Table 3
Ventilation rates ($m^3\,m^{-2}\,s^{-1}$) implemented with the simulation for each greenhouse structural design.

Air exchanges per hour (h^{-1})	Ventilation rate ($m^3\,m^{-2}\,s^{-1}$)		
N	A-frame	Arch-roof	Quonset
2	0.003	0.003	0.002
10	0.014	0.016	0.009
20	0.029	0.031	0.018
30	0.043	0.047	0.026
60	0.086	0.093	0.052
120	0.172	0.187	0.105

2.3. Mathematical model

The mathematical model described the state of the greenhouse environment and consisted of a system of three first-order differential equations which were derived from energy and mass balance principles. The parameters described by the state equations include: (1) T_{in}, air temperature (°C), (2) W_{in}, absolute humidity ($g_{water}\,kg^{-1}_{dry\,air}$) and (3) T_f, ground surface temperature (°C).

2.3.1. Energy balance equation

Energy balance equations can be derived under steady-state conditions for the thermal interaction of each of the greenhouse components. von Zabeltitz (1999) described the energy balance equations of four interacting components (air, plants, floor and roof) to define the resulting greenhouse environment. Fig. 3 contains a depiction of the energy and mass fluxes of a ventilated greenhouse. A simplified and augmented energy balance equation to describe the greenhouse environment can be expressed as (ASAE, 2003):

$$Q_{GRin} + Q_{Heater} = Q_{IV} + Q_{Glazing} \quad (1)$$

where Q_{GRin} is the global radiation absorbed within the greenhouse ($W\,m^{-2}$), Q_{Heater} is the thermal energy provided by the heating system ($W\,m^{-2}$), Q_{IV} is the energy exchange by infiltration and ventilation ($W\,m^{-2}$) and $Q_{Glazing}$ is the heat loss through the glazing ($W\,m^{-2}$). In the present project, we assumed that the net long wave radiation emitted or stored by plants, structure and glazing was negligible, as the magnitude of the radiation emitted by each of these components is of the same order and they cancel each other.

The global radiation absorbed inside the greenhouse Q_{GRin} was estimated with the following equation:

$$Q_{GRin} = \tau_c \cdot (1 - \rho_g) \cdot Q_{GRout} \quad (2)$$

where τ_c is the solar radiation transmittance of the glazing material (dimensionless), ρ_g is the reflectance of the solar radiation on the ground surface (dimensionless), and Q_{GRout} is the outside global radiation ($W\,m^2$).

The heat lost due to ventilation and infiltration (Q_{IV}) was computed with the following equation:

$$Q_{IV} = L \cdot E + q_v \cdot C_p \cdot \rho \cdot (T_{in} - T_{out}) \quad (3)$$

The two components in the right side of Eq. (3) define the latent and sensible heat losses, respectively, where L is the latent heat of vaporization of water ($J\,kg^{-1}$), E is the evapotranspiration rate within the greenhouse ($kg\,m^{-2}\,s^{-1}$), q_v is the ventilation rate ($m^3\,m^{-2}\,s^{-1}$), C_p is the specific heat of moist air ($J\,kg^{-1}\,K^{-1}$), ρ is the specific mass of air ($kg_{dry\,air}\,m^{-3}$), and $(T_{in} - T_{out})$ defines the air temperature difference, between inside and outside the greenhouse, respectively.

The heat flux lost through the glazing ($Q_{Glazing}$) was calculated with the following equation:

$$Q_{Glazing} = k \cdot w \cdot (T_{in} - T_{out}) \quad (4)$$

where k is the overall heat transfer coefficient ($W\,m^{-2}\,°C^{-1}$) and w is a ratio (dimensionless) of the glazing (A_{gl}) to ground (A_{fl}) surfaces.

The thermal radiation provided by the heating system (hot air) was defined by a constant function depending on the number of heaters (N_H) of predefined capacity (H_{cap}) and expressed per unit ground surface (A_{fl}) as

$$Q_{Heater} = N_H \frac{H_{cap}}{A_{fl}} \quad (5)$$

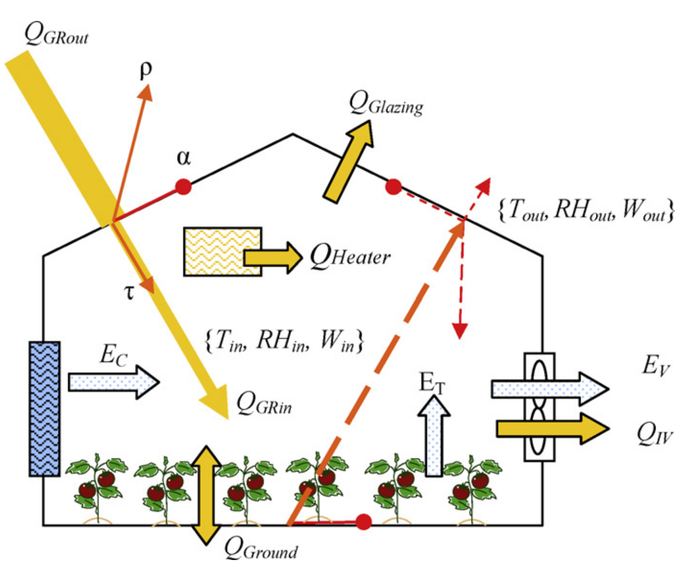

Fig. 3. Energy and water vapor fluxes within the greenhouse which define the energy and mass balance equations. See Table of Nomenclature for definitions of each parameter and variable.

2.3.2. Mass (water vapor) balance equation

For the mass balance of the air within the greenhouse it was assumed that no condensation occurred on the inside surface of the glazing, no evaporation resulted from the ground surface, and that the only sources of water to the greenhouse aerial environment was introduced by the evaporative cooling system (E_C) or by transpiration from the plants (E_T). The only water loss from the system was due to ventilation (E_V). Then, the mass balance equation was

$$E_C + E_T = E_V \tag{6}$$

Considering the two sources of water as one component ($E = E_C + E_T$), and expressing the water content within the greenhouse air as absolute humidity ($g_{water}\ kg^{-1}_{dry\ air}$), then the resulting mass balance equation was

$$W_{in} \cdot q_v \cdot \rho = W_{out} \cdot q_v \cdot \rho + E \tag{7}$$

where W_{in} and W_{out} were the absolute humidity of the air ($g_{water}\ kg^{-1}_{dry\ air}$), inside and outside the greenhouse, respectively, and E was the evapotranspiration (combined from plants and cooling system) rate ($kg\ m^{-2}\ s^{-1}$) within the greenhouse.

There are several evapotranspiration models for greenhouse crops reported in the literature and most of them include factors such as vapor pressure deficit (VPD), leaf temperature and wind speed. As described by Jolliet (1999), the factor that showed the highest correlation with transpiration was the inside solar radiation. It was assumed that transpiration was a linear function of the solar radiation within the greenhouse. The maximum transpiration rate $E_T = 8.9\ kg\ m^{-2}\ d^{-1}$ taken as a reference, corresponded to summer conditions in Tucson, AZ (Sabeh et al., 2006), as this was the location with the highest average daily insolation (Fig. 1). Solar radiation was normalized and integrated to the maximum E_T of reference. Crop transpiration at 15 min intervals was calculated with the following regressed equation:

$$E_T = \begin{cases} 0.0003 \cdot \tau_c \cdot Q_{GRout} + 0.0021 & \text{for large crop} \\ 0.00006 \cdot \tau_c \cdot Q_{GRout} + 0.0004 & \text{for small crop} \\ 0 & \text{for no crop} \end{cases} \tag{8}$$

Considering the greenhouse environment (air enclosed by the greenhouse glazing) as the control volume with homogeneous properties of air temperature and absolute humidity within its entire space, the system behavior could be described by the following first-order differential equations (Takakura and Fang, 2002; Takakura and Son, 2004):

$$\frac{dT_{in}}{dt} = \frac{1}{C_p \cdot \rho \cdot H}(Q_{GRin} + Q_{Heater} - L \cdot E - (T_{in} - T_{out}) \times (q_v \cdot C_p \cdot \rho + w \cdot k)) \tag{9}$$

$$\frac{dW_{in}}{dt} = \frac{1}{H \cdot \rho} \cdot (E - (W_{in} - W_{out}) \cdot qv \cdot \rho) \tag{10}$$

$$\frac{dT_f}{dt} = \frac{1}{C_s \cdot Z_0} \cdot \left(\alpha \cdot \frac{Q_{GRin}}{1000} + \varepsilon_f \cdot \sigma(\varepsilon_a \cdot aT_{in}^4 - aT_f^4) + h_s(T_{in} - T_f) + \frac{k_s(T_{bl} - T_f) \cdot 2}{Z_0 + Z_1}\right) \tag{11}$$

where C_p is the specific heat of air ($J\ kg^{-1}\ K^{-1}$), H is the average greenhouse height (m), and T_f is the temperature of the greenhouse ground (°C). Other coefficient definitions and values can be found in the Nomenclature section.

2.3.3. Numerical solution

The model, consisting of a system of three first-order differential equations (Eqs. (9)–(11)), was solved numerically using a classical fourth-order Runge–Kutta method as described by Chapra and Canale (2002):

$$y_{i+1} = y_i + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) \tag{12}$$

$$k_1 = f(x_i, y_i) \tag{13}$$

Table 4
Input and output parameters in the greenhouse environment model.

	Primary variables	Units	Derived variables	Units
Input	Time	s		
	Q_{GRout}	$W\ m^{-2}$	W_{out}	$g_{water}\ kg^{-1}_{dry\ air}$
	T_{out}	°C	Ws_{out}	$g_{water}\ kg^{-1}_{dry\ air}$
	RH_{out}	%	VPD_{out}	kPa
Output			Q_{GRin}	$W\ m^{-2}$
	T_{in}	°C	Ws_{in}	$g_{water}\ kg^{-1}_{dry\ air}$
	W_{in}	$g_{water}\ kg^{-1}_{dry\ air}$	RH_{in}	%
	T_f	°C	VPD_{in}	kPa

$$k_2 = f\left(x_i + \frac{1}{2}h, y_i + \frac{1}{2}k_1 h\right) \tag{14}$$

$$k_3 = f\left(x_i + \frac{1}{2}h, y_i + \frac{1}{2}k_2 h\right) \tag{15}$$

$$k_4 = f(x_i + h, y_i + k_3 h) \tag{16}$$

where y_i is the set of state variables in the model and h is the time step for evaluating the new y_{i+1} values for each equation. Data used in the simulations were at 900 s intervals, and h is adjusted from 7 to 112 s values to accommodate for different simulation scenarios. Data was interpolated to get intermediate values.

2.3.4. Initial conditions

The numerical solution of the differential equations of the greenhouse model required a set of initial conditions for each of the state variables, and for time $t = 0$, these were assumed to be $T_{in} = T_{out}$, $W_{in} = W_{out}$, and $T_f = T_{in}$, as provided within the climate data sets from each geographic location. Other variables not time-dependent were calculated directly. These variables included: (1) global radiation inside the greenhouse (Q_{GRin}), which was a function of the structure, glazing and/or shade curtains selected; (2) transpiration from plants (E_T), which was defined as a linear function of global radiation; (3) evaporation (E_C) from the cooling system, defined as a constant function when a cooling control function was selected. A set of input/output variables used in the simulation are listed in Table 4.

2.3.5. Control functions

The resulting greenhouse environment for a specific scenario depended not only on the external factors (climate), and the response of the inside conditions, but also on the control strategies implemented. Control strategies included reducing the greenhouse air temperature by using shade curtains, by ventilation or by evaporative cooling, or increasing the air temperature with heaters or by reducing the ventilation rate.

The simulation of the greenhouse environment was implemented for two general scenarios: (1) uncontrolled, where initial greenhouse configurations were selected and the control function of the actuators (shade curtains, ventilation, cooling system, and heaters) were inactivated; (2) controlled, where set-points for air temperature ($T_{spD} = 24$ and $T_{spN} = 18$ °C for day and night, respectively) were implemented and the control function for each component was defined with simple if-then rules to define the status (ON or OFF) for each component. The values for each of the control components for the ON and OFF conditions are listed on Table 5. For the ON condition, there were three levels of shade, five levels of ventilation, two levels of cooling, three levels of plant sizes, and two levels of heating. All OFF conditions were zero, except for Ventilation that was $2\ AC\ h^{-1}$ representing infiltration rate.

The control logic for the shade curtains was defined as if $Q_{GRout} > Q_{GRsp}$, then shades ON, else OFF, where Q_{GRsp}, was the

Table 5
Values for the ON-OFF condition for each of the control components for modifying the greenhouse environment.

Component	Units	Status	
		ON	OFF
Shade curtains	Percent of Shades (%)	30 50 70	0
Ventilation rate (Natural or Forced)	Air exchanges $N = (h^{-1})$	10 20 30 60 120	2
Cooling system	$E_c = (kg\,m^{-2}\,d^{-1})$[a]	7.4 14.8	0
Heating System	$H_{cap} = (kW)$	75 150	0

[a] Values taken from Sabeh et al. (2006).

threshold value for outside solar radiation, and was equal to 800 W m^{-2}.

The greenhouse air temperature was controlled by ventilation, evaporative cooling or by heating, depending whether the inside air temperature was greater or less than the air temperature set-point. For each case there were two conditions, depending on whether the air temperature was higher ($T_{in} > T_{sp}$) or lower ($T_{in} < T_{sp}$) than the set-points. In each situation the corresponding logic values were assigned to activate or de-activate the ventilation, the evaporative cooling or the heating systems accordingly.

3. Results and discussion

The greenhouse environment model was implemented in an interactive online web-based application (http://ag.arizona.edu/ceac/wge/simulator/) that incorporated user-selected information from a database of greenhouse designs, operations, and geographic climate conditions, and which graphically displayed dynamic changes in the greenhouse environment. This computer simulation program allowed users to simulate changes in the greenhouse–plant environment based on climate, structure, and environmental control choices (Fig. 4).

The numerical solution provided a dynamic response of the greenhouse climate to the outside climate conditions and for a particular greenhouse design. The design incorporated user-selected inputs for climate, structure, glazing, and environmental control systems. Each simulation demonstrated the response of a greenhouse system design over a 28-h period.

For the amount of user-selectable choices provided by the greenhouse environment simulator, there were 311,040 possible scenarios that could be demonstrated. The following greenhouse environment simulations were analyzed to show the potential of the simulator as an educational tool for demonstrating the physics of greenhouse systems and environmental control principles.

Although the results of the simulated scenarios were not validated with experimental measurements, they were verified with the logical responses obtained with the control strategies and the system implemented. As an educational tool the simulator allows for many scenarios that could be compared side-by-side enhancing the learning experience.

3.1. Greenhouse environment simulation with ventilation

In Fig. 5 and Table 6 the results of several simulated ventilation and cooling scenarios are displayed, showing the effect of reduced air movement within a greenhouse. The environment of an empty greenhouse (A-frame covered with glass) was simulated for the summer conditions at each of the four locations, and for different ventilation rates (for $N = 2$, 10, 20, 30, 60 and 120). The largest air temperature condition occurred when there was no air exchange ($N = 2$, air exchange due only to infiltration). Greenhouse air temperatures reached a maximum of between 35 and 40 °C in Columbus, OH, between 40 and 45 °C in Burlington, VT, and equal to or higher than 50 °C in Tucson, AZ and Fort Pierce, FL. By increasing the ventilation rate capacity, the greenhouse air temperature was reduced to nearly the outside conditions, which was still unfavorable (>35 °C) for growing plants. Therefore an artificial cooling mechanism was needed during the summer season, to maintain the desired greenhouse air temperature (24 and 18 °C for day and night time, respectively).

3.2. Greenhouse environment simulation with evaporative cooling

In the previous simulations it was demonstrated that artificial cooling, such as evaporative cooling system, was required to decrease the greenhouse air temperature. The cooling effect of the plant canopy on the greenhouse environment was not sufficient in extremely hot environments, as demonstrated in the following simulation scenarios. The sensible energy removed by plant transpiration, or evaporated from the cooling system (evaporative cooling pads, or fogging systems) into latent energy within the greenhouse environment is different at different ventilation rates. The cooling efficiency decreases at higher ventilation rates. Forty-two scenarios were simulated for an A-frame greenhouse structure covered with glass for spring season conditions in Tucson, AZ. In Fig. 6 each of the lines represents a simulation scenario (with plants size, $P = 0$, s, or L; evaporative cooling efficiency, $E = 0$, 1, or 2) at different ventilation rates (corresponding to $N = 2$, 10, 20, 30, 60 and 120 h^{-1}). The simulations scenarios include: (1) the cooling effect added by small (PsE0) and large (PLE0) plants with no cooling system, (2) the effect of the cooling system itself with no transpiration from plants, working at 50% (P0E1) and at 100% (P0E2) of its capacity, and (3) the combined effect of transpiration from large plants and the evaporation from cooling systems (PLE1 and PLE2).

Table 6
Summary data for each of the simulated scenarios (shown in Fig. 5) including different ventilation rates. Data include average outside and simulated values of air temperature, relative humidity, and daily PPF.

	AZ	FL	OH	VT
Outside				
PPF (mol m^{-2} d^{-1})	66.3	53.3	46.8	54.4
aT (°C)	24.3	25.3	20.5	24.9
RH (%)	19.4	73.6	61.0	51.9
N2				
aT	32.6	34.8	28.3	32.8
RH	13.0	44.5	38.8	33.6
N10				
aT	29.5	30.8	25.2	29.6
RH	14.6	54.4	46.0	39.9
N20				
aT	27.6	28.8	23.6	27.8
RH	15.7	60.7	50.7	43.8
N30				
aT	27.4	28.0	23.2	27.3
RH	15.7	63.2	51.5	45.0
N60				
aT	26.3	26.9	22.3	26.4
RH	16.7	67.3	54.3	47.5
N120				
aT	25.5	26.2	21.8	25.8
RH	17.5	70.0	56.0	49.2

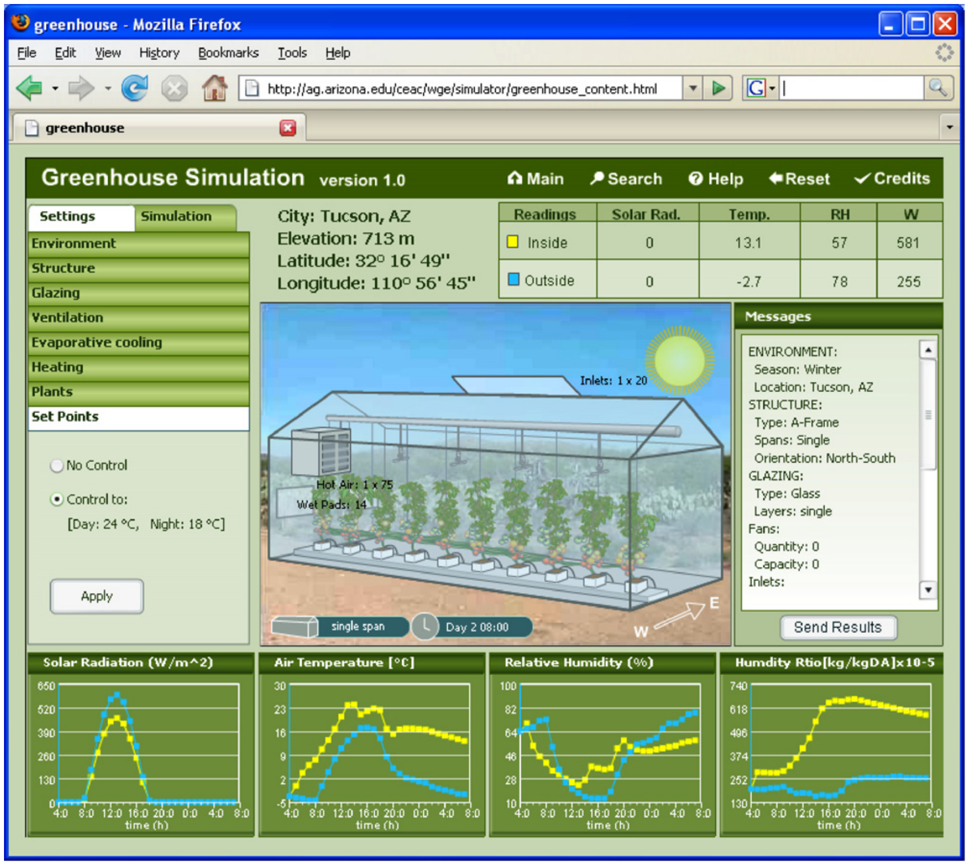

Fig. 4. Screen capture of the simulator after running a simulation of the greenhouse environment for winter conditions in Tucson, AZ.

The reference values for crop transpiration ($E_T = 8.9\,\mathrm{L\,m^{-2}\,d^{-1}}$) and evaporation from cooling system ($E_C = 14.8\,\mathrm{L\,m^{-2}\,d^{-1}}$) for summer conditions in Tucson, AZ were determined by Sabeh et al. (2006).

A data point, with the highest air temperature differential ($\Delta T = T_{in} - T_{out}$) in a greenhouse with no ventilation and no evapotranspiration, was taken as a reference in all simulations. This data point was used as a comparison of the air temperature differential drop when combining the cooling effect of plant transpiration, evaporation from a cooling system, and different ventilation rates. The reference point was taken at 13:15 h, when outside conditions ($T_{out} = 33.7\,^{\circ}\mathrm{C}$, $RH_{out} = 7.4\%$, and $Q_{GRout} = 1025\,\mathrm{W\,m^{-2}}$) provided the greatest cooling needs of the day. To reach the air temperature set-point (24 °C) it was required to have a $\Delta T = -9.7\,^{\circ}\mathrm{C}$ which was only reached at simulated low ventilation rates ($N = 2$ and 10), with maximum cooling efficiency and a large crop (PLE2). The simulated scenario with a large crop and a deficient cooling system (PLE1) at most will reach outside conditions that are not suitable for growing crops. The simulated scenarios with no evaporative cooling and different crop sizes (PnE0, PsE1 and PnE2) produced a greenhouse environment more extreme than the outside climate conditions.

3.3. Greenhouse environment simulation with shade curtains

The previous simulation scenarios were useful to show that, even with a cooling system, the desired greenhouse environment conditions may not be reached, especially during the hottest part of the day. A well-established practice in the greenhouse industry is the use of internal/external shade curtains or exterior paints to reduce the heat load during periods of excessive solar radiation. Shade curtains have the advantage of being controllable and deployed only when necessary. The following scenarios, which include the use of shade curtains, were simulated in an Arch-roof greenhouse design covered with a single layer of polyethylene film for summer conditions in Burlington, VT. The state variables (Q_{GRin}, T_{in}, T_f, RH_{in}, W_{in}, and VPD_{in}) resulting from the simulated scenarios are shown in Fig. 7 and summarized in Table 7. The simulation scenarios included the following combinations: S1 (SH = 0, P = 0, E = 0 and N = 2), S2 (SH = 30, P = L, E = 1, and N = 30), S3 (SH = 50, P = L, E = 1, and N = 20), and S4 (SH = 70, P = L, E = 2 and N = 20); where SH refers to the % of shade produced by the shade curtains selected, P refers to the plant size within the greenhouse (0 implies no plants and L is a large crop), E represents the evaporative cooling system capacity (0 = no cooling system, 1 = 50 % and 2 = 100% of cooling capacity), and N represents the ventilation rates expressed as air exchanges per hour. The effect of the shade curtains is visible on the solar radiation inside the greenhouse for the period of time when the curtains are deployed. During the daylight time the best greenhouse air temperature conditions were provided with the scenarios S3 and S4 for the time period of deployed shade curtains ($Q_{GRout} > 800\,\mathrm{W\,m^{-2}}$), after that S4 provided the best conditions (close to set-points) given the higher capacity of the cooling system. However, at night time S4 resulted in a sub-optimal plant environment with a saturated water

Table 7
Summary data for each of the simulated scenarios (shown in Fig. 7) that included the use of shade curtains. Data include average outside and simulated values.

	Outside	Simulated scenarios			
		S1	S2	S3	S4
PPF ($\mathrm{mol\,m^{-2}\,d^{-1}}$)	54.4	39.3	36.2	34.2	32.2
aT (°C)	24.9	33.4	24.4	23.4	21.0
RH (%)	51.9	32.7	60.0	65.3	79.8
W ($\mathrm{g_{water}\,kg^{-1}_{dry\,air}}$)	9.9	9.9	11.3	11.7	12.6
VPD (kPa)	1.7	3.9	1.3	1.1	0.5
T_f (°C)		19.2	17.9	17.7	17.4

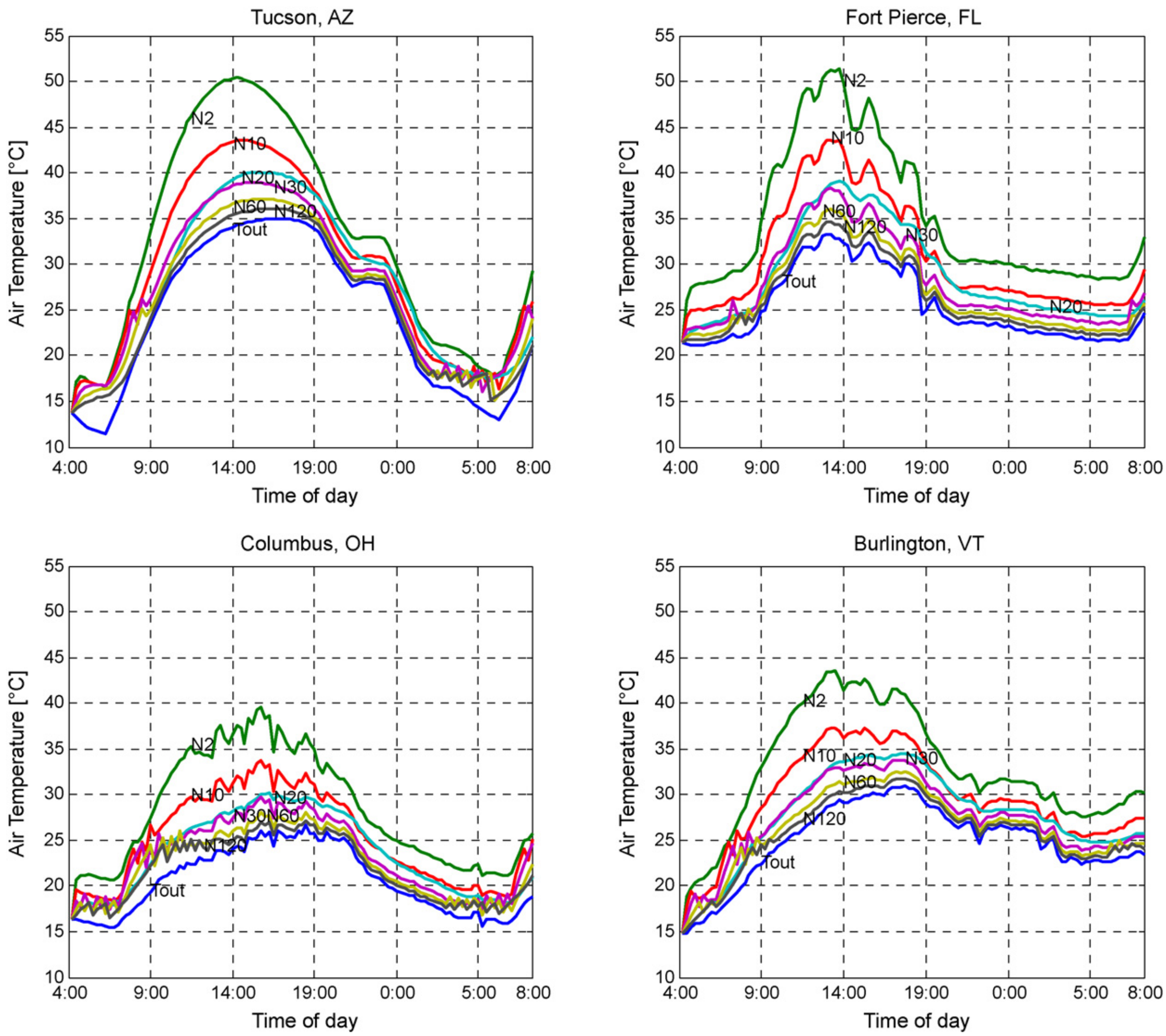

Fig. 5. Results of the greenhouse air temperature (T_{in}) simulation in a 28-h period for an A-frame structure covered with glass for each location (Tucson, AZ; Fort Pierce, FL; Columbus, OH; Burlington, VT) during summer conditions. No plants and no cooling system are included. Results include the effect of different ventilations rates (N10, N20, N30, N60 and N120), with a control function through the simulation period. T_{out} is the air temperature outside the greenhouse and N represent the air changes (AC h^{-1}). N2 is the air exchanges due to infiltration. Summary data can be found in Table 6.

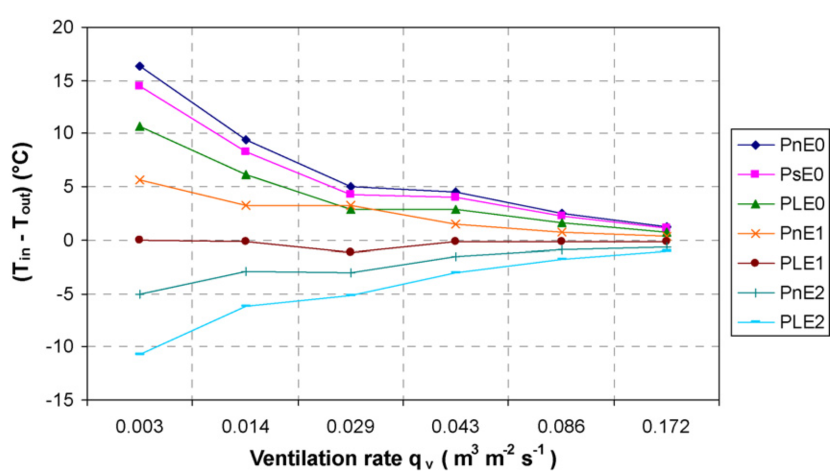

Fig. 6. Simulation results of an A-frame structure covered with glass and located in Tucson, AZ. Data points represent the air temperature differential ($T_{in} - T_{out}$) during the hottest part of the day for spring conditions at different ventilation rates and different scenarios. Outside climate conditions are T_{out} = 33.7 °C, RH_{out} = 7.4%, and Q_{GRout} = 1025 W m^{-2}. Simulation scenarios include no plants (Pn), small plants (Ps), large plants (PL), in combination with three evaporative cooling capacities, at 0, 50 and 100% (E0, E1, and E2, respectively).

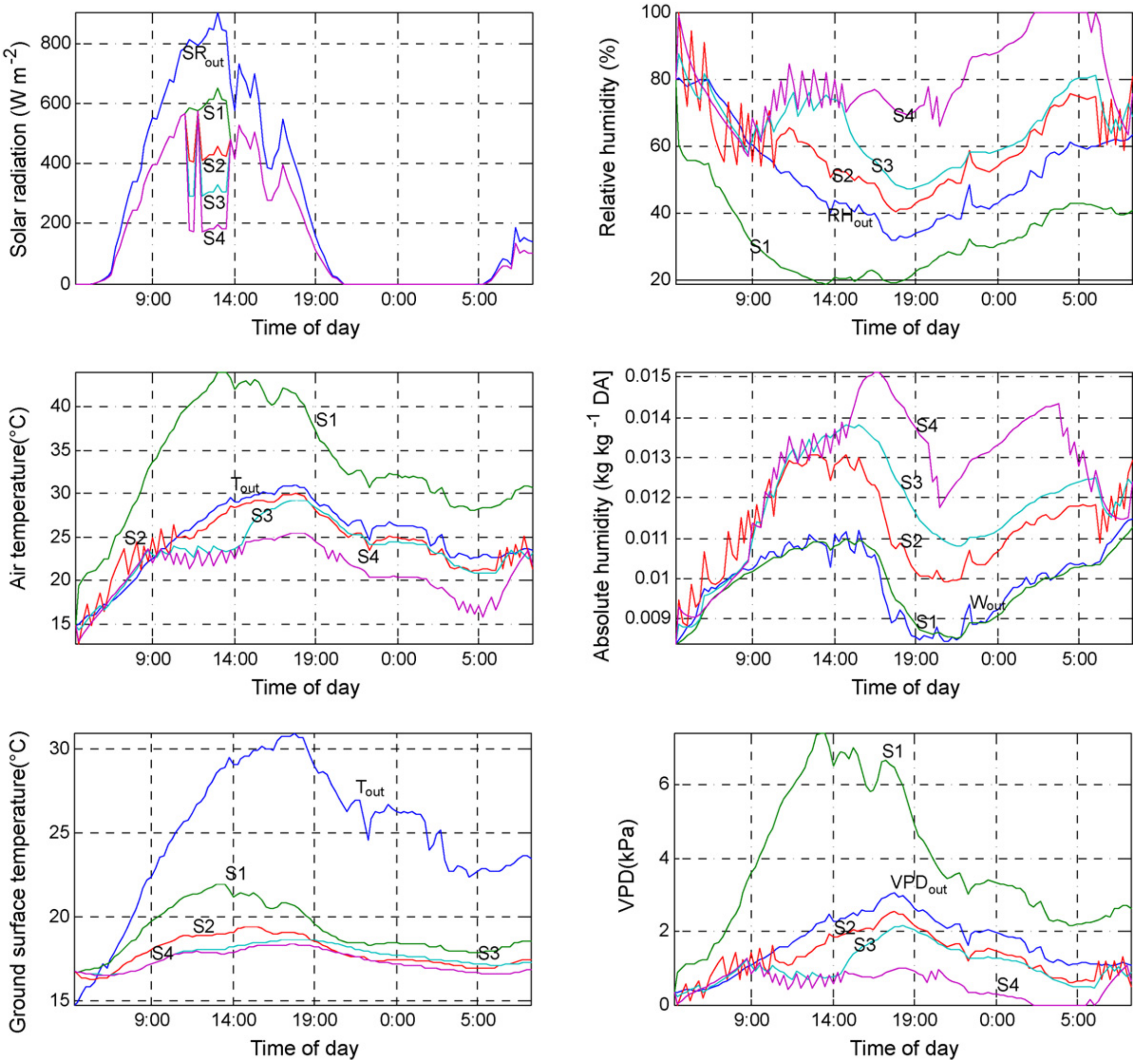

Fig. 7. Results of the greenhouse environment simulation of an Arch-roof structure covered with a single layer polyethylene film for summer conditions in Burlington, VT. Plots include values of the outside conditions and the results for each of the state variables at four different scenarios during a 28-h interval. Simulation scenarios include S1 (SH = 0, *P* = 0, *E* = 0 and *N* = 2), S2 (SH = 30, *P* = *L*, *E* = 1 and *N* = 30), S3 (SH = 50, *P* = *L*, *E* = 1 and *N* = 20), and S4 (SH = 70, *P* = *L*, *E* = 2 and *N* = 20), where SH refers to the % of shade produced by the shade clothes selected, *P* refers to the plant size within the greenhouse (0 implies no plants and *L* is a large crop), *E* represents the evaporative cooling system capacity (0 = no cooling system, 1 = 50% and 2 = 100% of cooling capacity), and *N* represents the ventilation rates expressed as air exchanges per hour. Summary data can be found in Table 7.

vapor environment due to the cooling system, which followed air temperature set-point.

3.4. Greenhouse environment simulation with heating

As shown in Fig. 1, three (VT, OH and AZ) of the four locations selected for simulations require supplementation of heat for some part of the year to maintain the chosen set-point. This occurs when the average daily air temperature drops below 12 °C. The simulation scenarios using a heating system were implemented in an A-frame structure covered with a single layer tempered glass for winter conditions in Columbus, OH. Fig. 8 includes outside climate conditions and the results for each of the greenhouse state variables at four different scenarios for three heating capacities, during a 28-h interval. Simulation scenarios include S1 (*P* = 0, *N* = 2 and H0), S2 (*P* = *L*, *N* = 2 and H0), S3 (*P* = *L*, *N* = 2 and H1), and S4 (*P* = *L*, *N* = 2 and H2). Where, H refers to the number of heating units selected (a single unit heater capacity was predefined as 75 kW). Under the extreme low temperatures, crop production during this season may not be economically feasible. Scenario S1 shows the increased air temperature during daytime resulting from the solar heat load and the reduced ventilation rate (N2). However, air temperatures were below freezing (−4 °C) during the daytime and even lower during the night time. Simulation scenario S2 implemented the same climate control mechanisms (N2 and H0), but now plants are included. Due to transpiration, the air temperature dropped 2 °C below the air temperature of the previous scenario, but now the greenhouse air reached saturation (RH = 100%) during the daytime when plants transpired more water due to solar radiation. Although air temperature was below freezing it was assumed plants were still alive and transpiring. Simulation scenario S3 included a heater (H1 = 75 kW) and the simulated greenhouse air temperature was above 0 °C, but did not reach the daytime and night time set-points. Due to the increased air temperature the air was saturated only a small portion during the daytime. Simulation scenario S4 included two heaters (H2 = 2 × 75 = 150 kW) and the simulated greenhouse air temperatures were close to the set-points. The increased water holding capacity of the greenhouse air at the simulated air temperatures resulted in no saturation and the RH was less than 50%. Results are also summarized in Table 8.

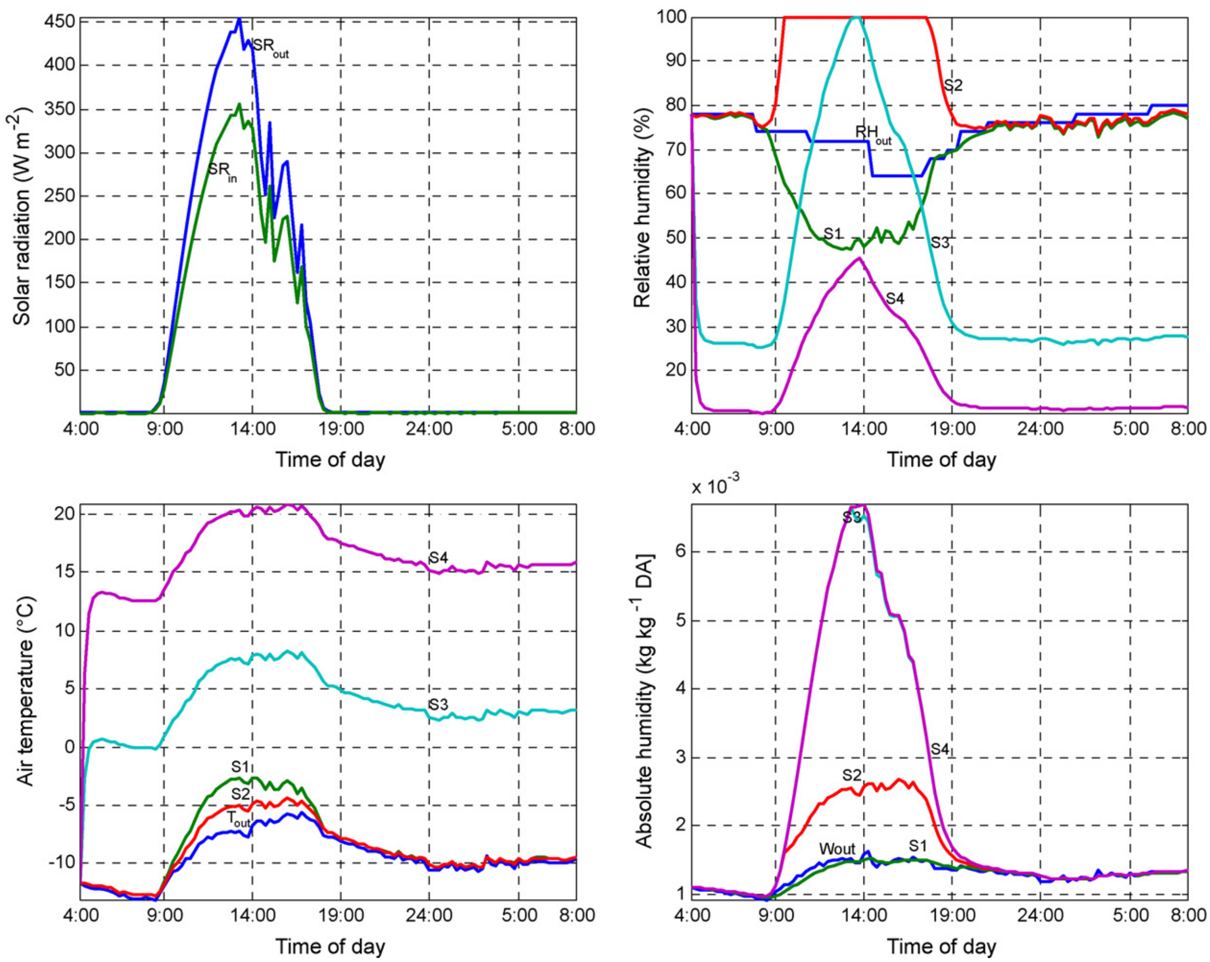

Fig. 8. Results of the greenhouse environment simulation of an A-frame structure covered with a single layer tempered glass for winter conditions in Columbus, OH. Plots include values of the outside conditions and the results for each of the state variables at four different scenarios considering three heating capacities, during a 28-h interval. Simulation scenarios include S1 ($P=0$, $N=2$ and H0), S2 ($P=L$, $N=2$ and H0), S3 ($P=L$, $N=2$ and H1), and S4 ($P=L$, $N=2$ and H2). P refers to the plant size within the greenhouse (0 implies no plants and L is a large crop), N represents the ventilation rates expressed as air exchanges, and H refers to the number of heating units selected (heater capacity is predefined at 75 kW). Summary data can be found in Table 8.

3.5. Limitations of the model

The numerical solution of the system of equations of the model depended on the initial condition imposed. In all cases the initial conditions were selected equal to the outside conditions. This was reflected on the lag response at the beginning of the simulation on each of the state variables. Several time step (h) values in the numerical implementation were predefined, however they do not perform well in all possible scenarios.

Input data to the simulator were established at 15 min intervals. However, for control purposes this was not an appropriate choice since the actuators response and operation required time intervals of a few seconds. This resulted in overshooting and undershooting on the state responses. Also, the control functions for ventilation and cooling were not staged and they operated at the maximum capacity in the ON position and to the minimum capacity in the OFF position.

Table 8
Summary data for each of the simulation scenarios (shown in Fig. 8) that included the use of heating systems. Data include average outside and simulated values.

	Outside	Simulated scenarios			
		S1	S2	S3	S4
PPF ($mol\ m^{-2}\ d^{-1}$)	18.2	14.3	14.3	14.3	14.3
aT (°C)	−9.5	−8.4	−8.9	3.6	16.1
RH (%)	74.3	68.3	84.1	42.3	18.8
W ($g_{water}\ kg^{-1}_{dry\ air}$)	1.3	1.3	1.6	2.3	2.3
VPD (kPa)	0.073	0.107	0.041	0.438	1.500
T_f (°C)	−9.5	−9.6	−9.7	−8.0	−6.3

4. Conclusion

The greenhouse environment simulator is a computer simulation program designed to be used as an educational tool for demonstrating the physics of greenhouse systems and environmental control principles. Given the amount of choices available through the animated user interface of the simulator, a large number (311,040) of possible scenarios can be replicated, making the simulation program helpful as an educational tool for demonstration purposes. We used the simulator to demonstrate how a greenhouse design could function for several climate conditions (for four seasons of four different locations), and the simulator also indicated what systems may be needed to achieve the desired environment conditions.

The simplified greenhouse environment model produced good approximations of the dynamic behavior of greenhouse environments with different configurations for 28-h simulation periods. The model also was incorporated into a web-based application where the simulation scenarios could be replicated without expensive simulation software.

Nomenclature

Symbol	Value	Units	Description
A_{fl}		m^2	Area of the greenhouse floor surface
A_{gl}		m^2	Area of the glazing surface
aT_f		K	Absolute temperature of the ground surface inside the greenhouse
aT_{in}		K	Absolute air temperature inside the greenhouse
C_p	1010	$J\,kg^{-1}\,K^{-1}$	Specific heat of moist air
C_s	2000	$kJ\,m^{-3}\,{}^\circ C^{-1}$	Heat capacity of the soil
E		$kg\,m^{-2}\,s^{-1}$	Evapotranspiration rate inside the greenhouse
H		m	Average greenhouse height
h		–	Time step in the numerical solution
H_{cap}		–	Heater capacity
h_s	25.2	$kJ\,m^{-2}\,{}^\circ C^{-1}\,h^{-1}$	Heat transfer coefficient at soil surface
k		$J\,m^{-2}\,{}^\circ C^{-1}\,s^{-1}$	Heat transmission coefficient of glazing
k_s	5.5	$kJ\,m^{-1}\,{}^\circ C^{-1}\,h^{-1}$	Thermal conductivity of the soil
L	2.5E6	$J\,kg^{-1}$	Latent heat of vaporization of water
N_H		–	Number of heaters
$Q_{Glazing}$		$W\,m^{-2}$	Heat loss through glazing
Q_{GRin}		$W\,m^{-2}$	Global radiation absorbed inside the greenhouse
Q_{Ground}		$W\,m^{-2}$	Heat flux from ground surface
Q_{GRout}		$W\,m^{-2}$	Global radiation outside the greenhouse
Q_{GRsp}	800	$W\,m^{-2}$	Set-point for shade curtain activation
Q_{Heater}		$W\,m^{-2}$	Heat flux from heating system
Q_{IV}		$W\,m^{-2}$	Heat loss by infiltration and ventilation
q_v		$m^3\,m^{-2}\,s^{-1}$	Ventilation rate
RH_{in}		%	Relative humidity inside the greenhouse
RH_{out}		%	Relative humidity outside the greenhouse
T_{bl}		$^\circ C$	Constant temperature at boundary layer, at 0.15 m
T_f		$^\circ C$	Ground surface temperature inside the greenhouse
T_{in}		$^\circ C$	Air temperature inside the greenhouse
T_{out}		$^\circ C$	Air temperature outside the greenhouse
T_{out24}		$^\circ C$	Daily average air temperature
VPD_{in}		kPa	Vapor pressure deficit inside the greenhouse
VPD_{out}		kPa	Vapor pressure deficit outside the greenhouse
w		–	Ratio of glazing surface to floor surface
W_{in}		$g_{water}\,kg^{-1}{}_{dry\,air}$	Absolute humidity inside the greenhouse
W_{out}		$g_{water}\,kg^{-1}{}_{dry\,air}$	Absolute humidity outside the greenhouse
W_{Sin}		$g_{water}\,kg^{-1}{}_{dry\,air}$	Absolute humidity at saturation inside the greenhouse
W_{Sout}		$g_{water}\,kg^{-1}{}_{dry\,air}$	Absolute humidity at saturation outside the greenhouse
Z_0	0.05	m	Soil depth of layer 0
Z_1	0.10	m	Soil depth of layer 1
α	70	%	Soil surface absorptivity
ε_a	75	%	Emissivity of air Layer
ε_f	95	%	Soil surface emissivity
ρ	1.2	$kg_{\,dry\,air}\,m^{-3}$	Specific mass of air
ρ_g	0.5	–	Reflectance of the solar radiation on the ground
σ	5.67E-8	$W\,m^{-2}\,K^{-4}$	Stefan-Boltzmann Constant
τ_c		–	Transmittance of the glazing material

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