Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
Available online at www.inia.es/sjar

Spanish Journal of Agricultural Research 2010 8(2), 285-298
ISSN: 1695-971-X

Greenhouses climate modelling. Tests, adaptation and validation of a dynamic climate model

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Abstract

Most greenhouse climate models are specific for a particular combination of greenhouse type, crop, region and weather conditions. Models are formulated and validated for those conditions and it is not easy to directly extrapolate them to other, different conditions. In order to use them the coefficients need to be calibrated by experimental work, followed by validation of the adapted model. The main purpose of this work was the application of a formal dynamic climate model, defined and validated for heated greenhouses in continental regions of Spain, to non heated greenhouses in a mild winter region at the coast of Portugal. The original model was tested, adapted and validated so it simulated the microclimate inside unheated greenhouses. The methodology used enabled the problems to be identified, the model to be modified in a systematic way and then re-run to determine the improved performance. The new model includes new properties for some boundary components and sub-models for ventilation and stomatal resistance applicable to this greenhouse-crop system and new expressions for the convection heat transfer coefficients. In the validation process predicted and measured variables were compared graphically to show trends in the data and by using statistical parameters to characterise model performance. The model was validated with data representing different weather, ventilation operation and tomato crop conditions. Good agreement between predicted and measured data was obtained. It has been proved that this model can be used to estimate the greenhouse climate conditions, based on the weather conditions and on the greenhouse-crop system characteristics.

Additional key words: convection heat transfer coefficients, nocturnal ventilation, unheated greenhouses.

Resumen

Modelado del clima de los invernaderos. Experimentación, adaptación y validación de un modelo climático dinámico

La mayor parte de los modelos climáticos de invernaderos son formulados y verificados para aquellas condiciones concretas en que fueron definidos, como son el tipo de invernadero, el cultivo y las características climáticas. Para aplicarlos en condiciones distintas, los coeficientes de los modelos deben ser calibrados, proceso seguido de la correspondiente validación del modelo adaptado. El objetivo principal del presente trabajo fue la aplicación de un modelo climático dinámico formal, definido y validado para invernaderos calefactados del interior de España con clima continental, a invernaderos no calefactados de la costa de Portugal con clima templado. La metodología empleada en este estudio permitió identificar los problemas del proceso de adaptación, modificando el modelo de una forma sistemática, para después determinar su comportamiento mejorado. El nuevo modelo climático incluye nuevas propiedades para algunos componentes de contorno, nuevos submodelos para la ventilación y la resistencia estomática del sistema invernadero-cultivo, y nuevas expresiones para los coeficientes de transferencia convectiva de calor. Para el proceso de validación, se compararon las predicciones y las mediciones de las variables ambientales del invernadero de una forma gráfica y mediante el empleo de estadísticos. El modelo fue validado con datos representando diferentes situaciones climáticas, operaciones del sistema de ventilación y condiciones del cultivo de tomate. El ajuste entre

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Received: 14-05-09; Accepted: 12-03-10.

los valores medidos y simulados fue bueno, lo cual prueba que el modelo puede ser usado para estimar el clima interior del invernadero, en función de las condiciones climáticas externas y de las características del sistema invernadero-cultivo.

Palabras clave adicionales: coeficientes de transferencia convectiva de calor, invernaderos sin calefacción, ventilación nocturna.

Introduction

The variables forming the greenhouse climate which are most important from the horticultural point of view are temperature, humidity, carbon dioxide concentration of the greenhouse air and the solar radiation intercepted by the crop. The air temperature depends on the energy losses and gains occurring at a given moment while the humidity depends on the gains and losses of water vapour. The climate produced in a greenhouse is the result of complex mechanisms involving the processes of heat and mass exchange. The internal climate is strongly dependent on the outside conditions, especially in unheated greenhouses (Linker and Seginer, 2004). In greenhouse climate models the parameters of the internal climate such as air, soil and crop temperatures, and air humidity are calculated using energy and water vapour balances for the various components of the system.

Interest in greenhouse research increased during the 1970s due to oil crises (Critten and Bailey, 2002), which turned energy saving into an important subject. This can be achieved by using the appropriate environmental control techniques at the right moment. For that, climate models are important tools, helping to predict the climate conditions inside greenhouses and also enabling the use of automatic control systems, which are the two main objectives of greenhouse climate modelling.

Static or steady state models have been developed mainly to describe the thermal behaviour of the greenhouse or to analyse the effect of environmental control techniques on the microclimate conditions (Bailey, 1981; Baille *et al*., 1985; Seginer *et al*., 1988). In general these models are less accurate due to their simplicity and involve only few parameters, but can be useful to evaluate environmental control techniques, while dynamic models are better in terms of accuracy, but involve more parameters (Harmanto *et al*., 2006), which could create a risk of divergence related to the choice of the initial conditions of the state variables (Boulard and Baille, 1993).

Dynamic models are important for simulating the greenhouse response on a small timescale, which requires the proper representation of the heat exchange processes between the interacting components. The heat and mass transfer coefficients are functions of the system variables and it is important that they are formulated under relevant conditions of the greenhouse situation (Bailey, 1991). Most of these models are complex, including various sub-models which describe the different physical phenomena occurring between the greenhouse components. Several authors developed simple dynamic greenhouse climate models (Boulard *et al*., 1996; Baille *et al*., 2006; Coelho *et al*., 2006; Harmanto *et al*., 2006; Perdigones *et al*., 2008) while others presented complex dynamic models (Bot, 1983; Pieters and Deltour, 1997; Zhang *et al*., 1997; Navas *et al*., 1998; Wang and Boulard, 2000; Abdel-Ghany and Kozai, 2006; Singh *et al*., 2006).

Most of the published greenhouse climatic models are adequate for heated greenhouses, typical of the northern countries. In fact, greenhouse climate models are specific for a greenhouse type, crop, region and weather conditions. The models are formulated and validated for those specific conditions and it is not possible to directly extrapolate them to different conditions, since they may produce erroneous predictions. In order to use them in different conditions, calibration of the model coefficients should be done by means of experimental work, followed by validation of the adapted model. Validation is a very important step in the modelling process since it tests the model performance. Several validation techniques were described by Sargent

Abbreviations used: CV (classical ventilation), EVA (ethyl-vinyl-acetate), *Gr* (Grashof number), h_c (convection heat transfer coefficient, W m^{-2} °C^{-1}), *k* (air thermal conductivity, W m^{-1} °C^{-1}), *l* (characteristic dimension of the surface, m), ME (mean error), MSE (mean square error or the errors variance), MST (total variance), NV (nocturnal or permanent ventilation), *Nu* (Nusselt number), PAR (photosynthetically active radiation), PE (polyethylene), *Pr* (Prandtl number), *Re* (Reynolds number), RMSE (root mean square error), r_a^2 (adjusted determination coefficient), *v* (air speed, m s^{-1}), Δt (temperature difference, °C)
Subscripts: *co* (cover), *cr* (crop), *gm* (growing medium), *ia* (inside air), *oa* (outside air), *s* (soil), *w* (wind).

(1998) and mentioned by Pee and Berckmans (1999). Irrespective of the validation method used, the purpose is to guarantee that the model predicts accurately the reality for which it was built.

The main objectives of this study were to test, adapt and validate a climate model for unheated greenhouses with a tomato crop in a mild winter climate region.

Material and methods

The greenhouse-crop system

The experiments took place in two plastic greenhouses with tomato crops located at the Instituto Superior de Agronomia, Lisbon. The structural material was galvanized steel and the covering material consisted of a 200 µm thick three layer co-extruded film (Triclair). The external layers were low density polyethylene (PE) and internal layer was ethyl-vinyl-acetate (EVA). The film was stabilized with an anti-UV agent. The inside layer had an anti-drop treatment and the outside layer an anti-dust treatment.

Each greenhouse had a floor area of 182 m^2, eaves height of 2.8 m and ridge height of 4.1 m; the orientation was north-south. The climate was controlled by natural ventilation, using continuous apertures located on the roof and side walls along the entire length of the greenhouses. Schematic drawings of an experimental greenhouse and the arrangement of the measuring equipment is shown in Figure 1.

The soil was a calcareous, red-brown clay soil (Cardoso, 1965). A spring tomato crop, *Solanum lycopersicum* L. (=*Lycopersicon esculentum* Miller), cv. *Zapata* from «Western Seed», was grown directly in the soil from the end of February until the end of July in 1998 and 2000. The tomato plants with 3-4 leaves were planted in twin rows (0.50 × 0.50 m), giving a plant density of 2.6 plants m^{-2}. The growing technique was the usual for greenhouse tomatoes in Portugal (Abreu and Meneses, 2000). Trickle ferti-irrigation tubes were located between each two rows of plants.

Management of natural ventilation was the main climate control technique used in these experiments. Two different natural ventilation treatments were randomly assigned to the greenhouses, one treatment to each

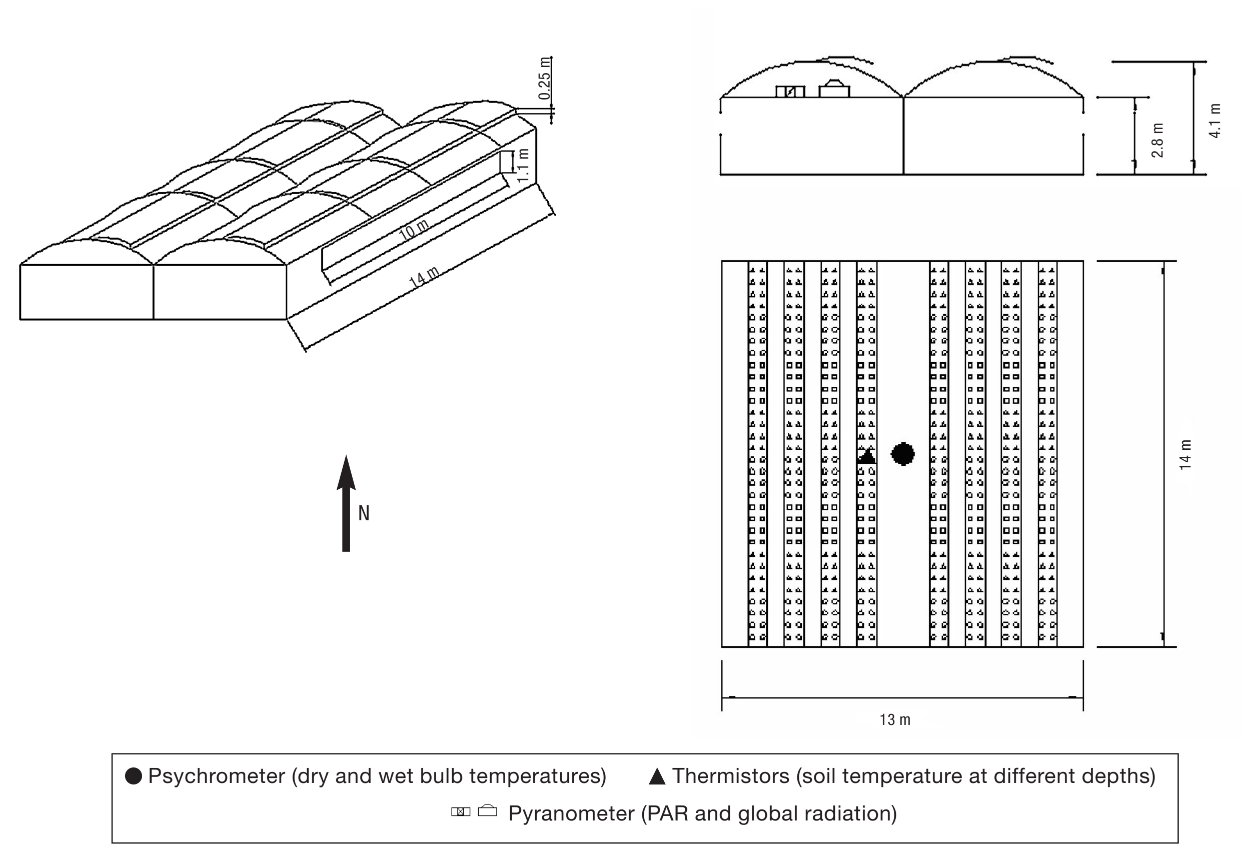

Figure 1. Schematic perspective, section and plan of an experimental greenhouse and location of the sensors.

greenhouse. One treatment was nocturnal or permanent ventilation (NV) during the day and night, while the other was classical ventilation (CV), in which the vents were opened during the day and closed during the night. Details of the two natural ventilation treatments applied in both years of the experiments are given in Baptista (2007). Ventilation management was achieved by manually controlling the side wall window opening by rolling the film around a steel pipe. Roof openings were opened or closed by manual activation using an electrical motor that operated the roof window via a rack and pinion drive.

Climatic data were measured with three meteorological stations, one located in the centre of each greenhouse and one outside. Air dry and wet bulb temperatures were measured every 10 min using a ventilated psychrometer fitted with PT100 sensors (Thies Clima, Goettingen, Germany) located at a height of 1.5 m. Global and photosynthetically active radiation (PAR) was measured at 10 s intervals using a Schenk 80101 pyranometer (P. Schenk, Wien, Austria) and a special PAR sensor SKP210 (Skye Instruments Ltd., Powys, UK), respectively. The radiation sensors were located at heights of 2.8 m inside the greenhouse and 4.3 m outside. Wind speed was recorded every 10 s by an anemometer located at a height of 4.5 m (Thies Clima, Goettingen, Germany). Growing medium temperature was measured at several depths in the NV greenhouse and at a depth of 20 cm outside and inside the CV greenhouse. In all the cases soil temperatures were recorded every 10 min using thermistors (Delta T-Devices, Cambridge, UK). Leaf temperature was measured every minute using infrared thermometers (Everest Interscience Inc, Tucson, USA). The cover temperature was measured every minute using a thermocouple 0.2 mm in diameter, attached directly to the inner film surface.

Growing medium moisture content was measured every 10 min using electronic tensiometers (UMS GmbH, Munich). The water draining from a lysimeter was discharged through a buried pipe to a Rain-o-Matic rain gauge (Pronamic, Denmark) placed outside the greenhouse and protected from the external climate. It was measured every 10 min. Data about water flow and duration of irrigation were recorded to compute the quantity of water supplied to the lysimeter, which was the same amount supplied to the rest of the greenhouse on a unit area basis.

All data were averaged and recorded on an hourly basis using two data logger systems from Delta-T Devices.

Description of the original climate model

A model was required to predict the climate in unheated greenhouses in a region with mild winter conditions. Most of published climate models were developed in northern countries for heated greenhouses. The dynamic model selected had been developed and validated (Navas, 1996; Navas *et al.*, 1998) for a greenhouse with a gerbera crop located in the Mediterranean climate conditions of the centre of Spain. This particular model was selected from a number of models developed for heated greenhouses because: i) it was developed and validated for similar climate conditions of the present work; ii) the model was formulated considering all the requirements for dynamic models (identification of the process and boundary components as all the correspondent heat transfer processes, mathematical and physical formulation and sensitivity analysis); iii) the simulation program could be operated in any PC, the mathematical algorithms were well identified and the required simulation period was small (results for 1 h simulation taking 5 s).

The model is basically quasi-one-dimensional and single layer, the greenhouse is divided in five components: growing medium, soil, crop, cover and inside air. The energy fluxes between the components of the greenhouse model are described by the exchange of sensible heat, latent heat and radiation, per unit area. The dynamic characteristics of the model arise from consideration of the heat storage in the growing medium and soil, which requires these components to be subdivided into six layers (1 to 6) to describe their thermal capacities correctly.

Energy balance equations are formulated for each of the five greenhouse components. The growing medium, soil, crop and cover are characterised by their temperature, so only thermal balance equations are defined. On the contrary, the inside air is defined by the temperature and humidity, so thermal and moisture balance equations are formulated for this component. As a result, the model is composed of sixteen energy balances, making up a set of six algebraic and ten first-order differential equations. The fourth-order Runge-Kutta method was used to solve the differential equations numerically.

The greenhouse system is divided in process and boundary components. The variables simulated (process components) by the model are the inside air temperature and relative humidity, the temperatures of the crop, cover, soil and growing medium. The boundary components are the characteristics of the outside air (temperature and relative humidity), wind speed, solar radiation, temperatures of the deep growing medium and soil, growing medium and soil moisture contents and the characteristics of the environmental control systems. The model is parameterized by a set of constants relating to geometrical, thermal, optical and other properties of the greenhouse-crop system. The simulation time interval is 1 min, which is comparable with the time constants of the model process components with low thermal capacities. A full description of all equations, the model and the DPG (Dynamic Performance of Greenhouses) programme was given by Navas (1996).

Methodology

Since the climate model was developed for different conditions than those which occurred in this work, it was necessary to test it with the new conditions and make adjustments as necessary. The methodology followed to adjust the model was: i) to identify the problems by using the original climate model with data recorded during the experiments; ii) to modify the model in a systematic way; iii) to compare the results obtained from simulations with the model before and after the modifications; and iv) to validate the final climate model, using different experimental data from both years of experiments.

The model was considered adequate when used with the specific conditions of weather, crop and greenhouses used in our experiments. Air properties such as density, enthalpy, absolute humidity, vapour pressure at saturation, dew point temperature, psychrometric constant, latent heat of vaporization, thermal conductivity, specific heat, and kinematic viscosity and the water specific heat and thermal conductivity are calculated in the model as a function of the temperature. The sky temperature is determined as a function of the outside air dry bulb and dew point temperatures. The aerodynamic resistance of tomato leaves is calculated as a function of the inside air density, specific heat and the crop to air convection heat transfer coefficient. A full description was given by Navas (1996) and Baptista (2007).

Determination of convection heat transfer coefficients is complex mainly due to the high quantity of influencing factors, as the surface shape, position and the nature of the involved heat flows (Bailey and Meneses, 1995). Convection analysis can be simplified by using non dimensional groups as the Grashof, Reynolds, Prandtl and Nusselt numbers. The methodology used in this case enabled a study of the nature of the convection and the type of flow as a function of the specific greenhouse characteristics and environmental conditions. The procedure was the following: i) to select characteristic days with different conditions of air temperature, wind speed, solar radiation, inside air speed and ventilation management; ii) to calculate the Grashof and Reynolds numbers; iii) to determine whether the flux was laminar or turbulent, depending on the sizes of Gr and Re for free or forced convection, respectively; iv) to calculate the Nusselt number using expressions obtained experimentally as a function of Gr & Pr or Re & Pr depending on whether the convection was free, forced or mixed and the type of flux, and v) to calculate the convective heat transfer coefficient. Depending on the analysed component, the coefficient was related with temperature difference, wind speed or inside air speed.

Validation process

Predictive validation was performed. The model was used to predict the behaviour of the process components and then the experimental and predicted data were compared for selected days of 1998 and 2000. The experimental data used for validation had not been used when modifying and calibrating the parameters of the model. The data used to validate the climate model were recorded each minute, between 12 and 15 May and 15 and 18 June in 2000. During 1998, data were recorded on an hourly basis on 29 April, 5 June and 6 July and interpolated to provide values at 1 minute intervals using the cubic spline method (Stoer and Bulirsch, 1980).

Table 1 shows the ventilation characteristics for the days used to validate the model. The model was run for several days with the relevant boundary conditions and constants for the greenhouse-crop system. The predictions obtained for several greenhouse components were compared with the measured data. The comparisons were made graphically to show trends in the data and statistical parameters were used to characterise model performance, such as mean error (*ME*), root mean square error (*RMSE*), adjusted determination coefficient (r_a^2) and maximum absolute error.

Table 1. Ventilation opening dimensions: height (m) and area (m^2, in parentheses)

Year	Date	Nocturnal ventilated greenhouse		Classical ventilated greenhouse	
		Day	Night	Day	Night
1998	29 April	0.41 (8.2)	0.10 (2)	0.41 (8.2)	0 (0)
	5 June	0.52 (10.4)	0.20 (4)	0.52 (10.4)	0.20 (4)
	6 July	0.52S+0.25R[1] (17.4)	0.52S+0.25R (17.4)	0.52S+0.25R (17.4)	0.52S+0.25R (17.4)
2000	12-15 May	0.54 (10.8)	0.22 (4.4)	0.54 (10.8)	0 (0)
	15-18 June	0.75 (15)	0.75 (15)	0.75 (15)	0.75 (15)

[1] S: side openings. R: roof openings.

$$ME = \frac{\sum_{i=1}^{n}(y_i^{'} - y_i)}{n} \quad [1]$$

$$RMSE = \sqrt{MSE} \quad [2]$$

$$r_a^2 = 1 - \frac{MSE}{MST} \quad [3]$$

where *MSE* is the mean square error or the errors variance, calculated by Eqn [3]. *MST* represents the total variance, $y_i^{'}$ is the predicted value, y_i the observed value and *n* the number of observations.

The emissivity (ε) and reflectivities (φ) of the growing medium and soil were determined as a function of the moisture content (x_{wa}) (Horton, 1989), changing between 0.91 and 0.97 and between 0.10 and 0.25, respectively. The crop leaf area index (LAI) was between 2.4 and 4.4, the cover material emissivity was 0.60 and the transmissivity 0.37 (measured in laboratory at Silsoe Research Institute). The greenhouse solar transmissivity was between 0.71 and 0.68 for the 1998 and 2000 experiments, respectively.

Results and discussion

Testing the original model

As the first step, the climate model developed by Navas (1996) was used to simulate the climate of the greenhouses used for this research. The goal was to determine if the model fitted the data well, and if not to identify the aspects that should be corrected. For this, the model was used without any modification, but with the boundary conditions for the Lisbon greenhouses, the tomato crop and local climate characteristics.

Baptista *et al.* (2000, 2001) presented results of simulations for several days in different months based on the external climatic data, and parameters related with the growing medium, the covering material and the crop. The distinction between the growing medium and soil was on the basis of moisture content, considering the soil as the area of dry ground and the growing medium as the wet area, which corresponded to the area occupied by the crop. Since it was a first approximation and due to the inputs of the model, it was necessary to make some assumptions and to estimate some parameters which had not been measured during the 1998 experiments. The growing medium moisture content was estimated using methods described by Rawls *et al.* (1992) and Allen *et al.* (1994). The inside air speed was estimated using an approach similar to one used by Wang *et al.* (1999), considering the inside air speed as a function of the wind speed and the area of the open vents (Baptista *et al.,* 2000).

Table 2 presents the *RMSE* and the *ME* between the predicted and measured values for each of the analysed days. As expected, the results of this first approximation revealed some problems, which were related mainly to the different crop and local conditions. When comparing predicted and measured values, agreement was poor for the temperature of the crop, the first layers of the growing medium and the soil, and for the relative humidity, while the inside air and cover temperatures presented reasonable agreement. It was evident that some improvements were required to make the climate model suitable for our specific conditions.

The simulated crop temperatures were much higher than the measured values, especially during the day which could be due to an incorrect model estimation of the heat exchange by transpiration. This seems reasonable since the crop characteristics incorporated in the model were for a gerbera crop. Others aspects that could contribute to the results were the expression to determine the convection heat transfer coefficient, the

Table 2. Root mean square error (*RMSE*) and mean error (*ME*) between the values given by the original model and those measured (some days of 1998)

		29 April	09 May	15 May	20 May	05 June	21 June
Inside air temperature (°C)	*RMSE*	1.27	2.45	1.14	2.31	0.87	1.93
	ME	0.01	1.27	0.25	1.05	0.48	1.66
Inside air relative humidity (%)	*RMSE*	4.60	10.43	11.01	8.30	8.10	9.34
	ME	2.05	3.35	8.01	–2.13	–0.69	–7.64
Crop temperature (°C)	*RMSE*	2.66	7.02	4.18	5.46	4.96	7.34
	ME	1.20	5.19	2.74	4.04	3.46	5.48
Cover temperature (°C)	*RMSE*	1.27	2.32	1.61	2.16	1.61	2.20
	ME	–0.16	–1.32	–0.79	–1.14	–0.32	–0.48
Growing medium temperature (layer 3) (°C)	*RMSE*	0.52	4.41	3.42	3.88	2.99	3.11
	ME	0.30	2.41	1.57	2.32	1.54	1.19
Growing medium temperature (layer 5) (°C)	*RMSE*	0.28	1.59	1.38	1.34	1.02	1.43
	ME	0.01	0.56	0.54	0.34	0.39	0.63
Soil temperature (layer 3) (°C)	*RMSE*	7.60	9.72	8.29	8.26	9.96	10.76
	ME	4.52	5.84	4.94	5.18	6.54	6.82

leaf area index and the proportion of the growing medium which was receiving solar radiation and then emitted thermal radiation to the crop.

Predicted surface growing medium and soil temperatures were also higher than the measured values, with bigger differences during the day, indicating excessive heat gains by solar radiation. This was related to shading by the crop. Also, during the night the poor simulation results could be due to incorrect physical soil properties, *e.g.* thermal capacity, thermal conductivity or again the convection heat transfer coefficient.

Results of the simulations for the relative humidity were in general not good, with errors higher than 20% mainly during the day. Of course this behaviour is directly related with crop transpiration, evaporation from the growing medium, condensation and ventilation.

The model predicted reasonably well the values for the inside air and cover temperatures. However, for the air temperature, it showed that after opening or closing the vents the model reacted too much and took about 2 h to readjust. Some improvements could be expected with the introduction of a ventilation sub-model more appropriate for the greenhouses and again with more suitable convection heat transfer coefficients.

In conclusion, the modifications required were mainly related to the ventilation and transpiration sub-models, and the convection heat transfer coefficients.

Modification of crop, ventilation and heat transfer coefficients

After identifying these short comings the second phase consisted of introducing step by step changes to the model, re-running the simulation with the revised model and analysing the results. The first changes were:

(i), incorporate a stomatal resistance expression developed for tomato crops which related the internal resistance (r_i) to solar radiation (SR_i) and leaf vapour pressure deficit (VPD_{leaf}) (Jolliet and Bailey, 1992):

$$r_i = \left[0.0041 \times (1 - 0.66 \times (\frac{200}{SR_i + 200}) - 0.22 VPD_{leaf}) \right]^{-1} \quad [4]$$

and (ii), substitution of the Sherman and Grimsrud (1980) ventilation model, which is not defined for continuous apertures, by other ventilation sub-models developed by Boulard and Baille (1995) and by Boulard *et al.* (1997) for continuous openings.

Boulard and Baille (1995), for greenhouses equipped with only roof or side vents, showed that ventilation rate (V) can be simulated with good accuracy by a model combining wind and buoyancy effects:

$$V = \frac{A}{2} C_d \left(2g \frac{\Delta t}{T_o} \frac{H}{4} + C_w v_w^{\,2} \right)^{0.5} \quad [5]$$

where A represents the opening area, C_d is the discharge coefficient of the opening, C_w is the global wind pressure coefficient, g is the acceleration of gravity, H represents the vertical height of the opening, T_o is the outside temperature in Kelvin, v_w is the wind speed and ρ is the air density. The first term in parenthesis represents the thermal effect and the second one the wind effect. In the case of a greenhouse equipped with both roof and side vents, the ventilation rate is given by Boulard *et al*. (1997):

$$V = \frac{A}{2} C_d \left(2g\varepsilon^2 \frac{\Delta t}{T_o} \frac{h}{2} + C_w v_w^{\,2} \right)^{0.5} \qquad [6]$$

The factor ε represents the relative importance of roof and side areas and h the vertical distance separating the centres of the roof and side vents.

Ventilation coefficients, C_d and C_w, are characteristic of the ventilation performance of each greenhouse type and have been identified by several authors. Compilation of these values for several types of greenhouses can be found in Boulard and Baille (1995) and Roy *et al*. (2002).

At this stage it was also assumed that the two sides of the leaf contribute to heat exchange by transpiration, since stomata are present on both sides of tomato leaves (Stanghellini, 1987; Boulard *et al.*, 1991). After this procedure, simulations were made for some days of 1998 and 2000. In general, the inside air temperature was predicted with greater accuracy than before while for most days simulation of relative humidity was worse. Crop temperature simulation improved slightly, indicating a better adaptation of the stomatal resistance submodel than before. However, the results showed that the modifications did not significantly improve the simulations.

The next step was to calculate the convection heat transfer coefficients (h_c), based on the nature of convection (free, forced or mixed) and the type of flow (laminar or turbulent), using the Nusselt number (Nu):

$$h_c = \frac{kNu}{l} \qquad [7]$$

where k is the air thermal conductivity and l the characteristic dimension of the exchange surface. The Nusselt number is a function of the Grashof (Gr) and Prandtl (Pr) numbers if convection is free and of the Reynolds (Re) and Prandtl numbers if it is forced (Monteith, 1973). However, in greenhouses most of the convection heat exchange is due to mixed convection with both processes involved (Stanghellini, 1987; Papadakis *et al.*, 1992). In this case Stanghellini (1987, 1993) suggested that Nu_m was a function of the Grashof and Reynolds numbers.

To determine h_c it was necessary to establish some criteria which allowed identification of the nature of the convection and the type of flux. Comparison between Gr and Re enables a decision to be made on which force is responsible for the heat exchange. Monteith (1973), Bot and van de Braak (1995) and Roy *et al*. (2002) suggested some relations between Gr and Re which identify the conditions for each of the processes. Differentiation between laminar and turbulent flux was based on the magnitude of the Grashof number in the case of free convection ($Gr < 10^8$ laminar, $Gr \geq 10^8$ turbulent) and the Reynolds number for forced convection ($Re < 10^5$ laminar, $Re \geq 10^5$ turbulent) (Monteith, 1973; Roy *et al*., 2002).

Several days were selected for determination of the convective heat transfer coefficients which covered ranges of external temperature, wind speed, solar radiation, crop size and internal air speed. A full description can be found in Baptista (2007).

Table 3 presents the expressions for the convection heat transfer coefficients, which resulted from a systematic analysis of the experimental data and these expressions were introduced into the climate model. Concerning the heat transfer between the cover and the outside air, the convection could range from natural through mixed to forced, depending on temperature difference and wind speed. However, most of the time it was in the region of mixed convection, which is agreement with Kittas (1986), Papadakis *et al.* (1992) and Navas (1996). The flux was mainly turbulent ($Gr \geq 10^8$ and $Re \geq 10^5$).

Concerning the internal components, usually the most relevant factor is greenhouse ventilation, because of the influence on inside air speed. On the selected days, the maximum inside air speed was 0.2 m s^{-1}, even with the vents opened. The nature of the convection was found to be predominantly free and the flux was always turbulent.

For the crop, the nature of the convective process is also influenced by the crop characteristics, such as leaf size and plant height. The selected days covered a range of conditions, different ventilation management and stages of crop development. It is important to mention that the convection heat transfer coefficient in this case refers to the leaves and not to the crop, since the leaves are the main element that exchange heat with surroun-

Table 3. Convection heat transfer coefficients for the various greenhouse components

h_c (W m^{-2} °C^{-1})	n	*RMSE*
$h_{c,co\to oa} = 2.020 + 0.084\left\|t_{co} - t_{oa}\right\| + 2.985v_w$	192	0.379
$h_{c,ia\to co} = 1.470\left\|t_{ia} - t_{co}\right\|^{0.32}$	192	0.022
$h_{c,gm\to ia} = 1.215\left\|t_{gm} - t_{ia}\right\|^{0.32}$	192	0.022
$h_{c,s\to ia} = 1.464\left\|t_s - t_{ia}\right\|^{0.32}$	192	0.017
$h_{c,cr\to ia} = 2.349 + 0.046\left\|t_{cr} - t_{ia}\right\| + 32.703v_{ia}$	288	0.141

dings. To obtain the convection heat transfer between the crop and the air, the expression obtained should be multiplied by 2LAI, since both sides of the leaves contribute to the convection heat exchange. Most of the time convection was mixed and the flux was found to be laminar.

Validation

In order to evaluate the overall accuracy of the estimates made by the model an analysis was performed with all validation data and the overall values of *ME* and *RMSE* were calculated and are presented in Table 4. The air temperature is simulated accurately, with overall values of *ME* of 0.3°C and *RMSE* of 1.6°C, which represents values accepted as good by several authors (Wang and Boulard, 2000; Cunha, 2003; Luo *et al*., 2005; Coelho *et al*., 2006). Air relative humidity, accepted as the most difficult parameter to estimate due to the dependence of the air temperature, showed *ME* of –0.8% and *RMSE* of 7%, these results are in accordance with others published by Zhang *et al*. (1997), Navas *et al*. (1998) and Salgado and Cunha (2005).

Crop temperature was well simulated with overall values of *ME* of 0.4°C and *RMSE* of 2.2°C, which is in agreement with Zhang *et al.* (1997) and Singh *et al*. (2006). The cover temperature was also predicted with good results, particularly if we accept this is another difficult parameter to measure because of sensor exposure to solar radiation. The *ME* was found to be 0.3°C and the *RMSE* was 2.9°C, which is lower than other published results (Navas, 1996; Singh *et al*., 2006).

For the growing medium, the surface layer gave the worst result, with *ME* and *RMSE* values of –1.5 and 2.4°C, respectively. The negative mean error indicates that predicted values were lower than those measured. This occurred mainly during the day and is explained by possible sensor exposure to solar radiation. The results obtained for layers 2 and 3 showed better results, with *ME* values between –0.2 and –0.5°C and *RMSE*

Table 4. Summary of the results for all validation days

	Night		Day		24 h	
	ME	*RMSE*	*ME*	*RMSE*	*ME*	*RMSE*
t_{ia} (°C)	0.52	1.28	0.07	2.00	0.32	1.60
RH_{ia} (%)	2.32	6.90	–5.39	7.10	–0.76	6.98
t_{cr} (°C)	–0.08	1.59	1.20	3.00	0.40	2.24
t_{co} (°C)	–0.23	1.91	1.00	3.84	0.28	2.85
t_{gm1} (°C)	–1.26	2.29	–1.81	2.52	–1.46	2.35
t_{gm2} (°C)	–0.54	1.35	0.25	1.03	–0.22	1.23
t_{gm3} (°C)	–0.39	0.89	–0.71	1.04	–0.50	0.94
t_{gm4} (°C)	–0.10	0.56	–0.03	0.50	–0.07	0.54
t_{gm5} (°C)	–0.04	0.35	0.35	0.50	0.11	0.42
t_{gm6} (°C)	–0.10	0.24	0.09	0.20	–0.02	0.23

values between 0.9 and 1.2°C, which are in the same range as those presented by Navas (1996) and Wang and Boulard (2000). Growing medium temperatures for layers 4, 5 and 6 present values for the *ME* between –0.02 and 0.1°C and for the *RMSE* between 0.2 and 0.5°C, being in accordance with Navas (1996) and show the very good agreement and the power of the model to estimate the growing medium temperature.

Table 4 permits the comparison of the model performance for the day and night periods. It is clear that the model fitted the data better during the night than during

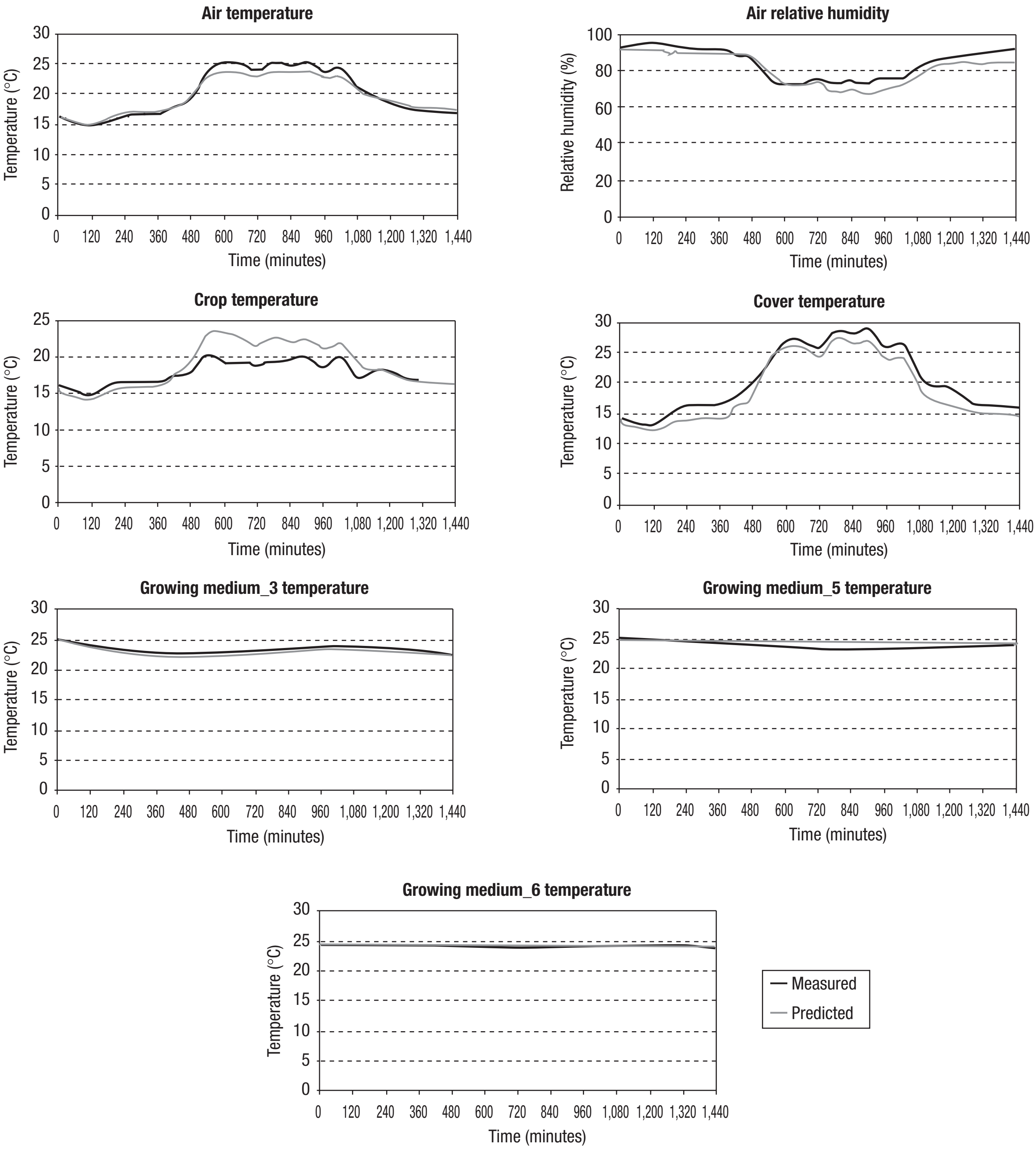

Figure 2. Results of the simulation for 6 July 1998 for the NV greenhouse.

the day. These differences are particularly visible for the air, crop, cover and surface growing medium temperatures and for the relative humidity, with in general, the values of the *RMSE* being lower for the night period. This is related with the more complex day energy balance. For growing medium layers 2 to 6 the model performances during the day and night were similar.

In summary, the predictions agreed well with the recorded data, showing a slightly better performance during the night. It was shown that overall model performance is good and independent of ventilation

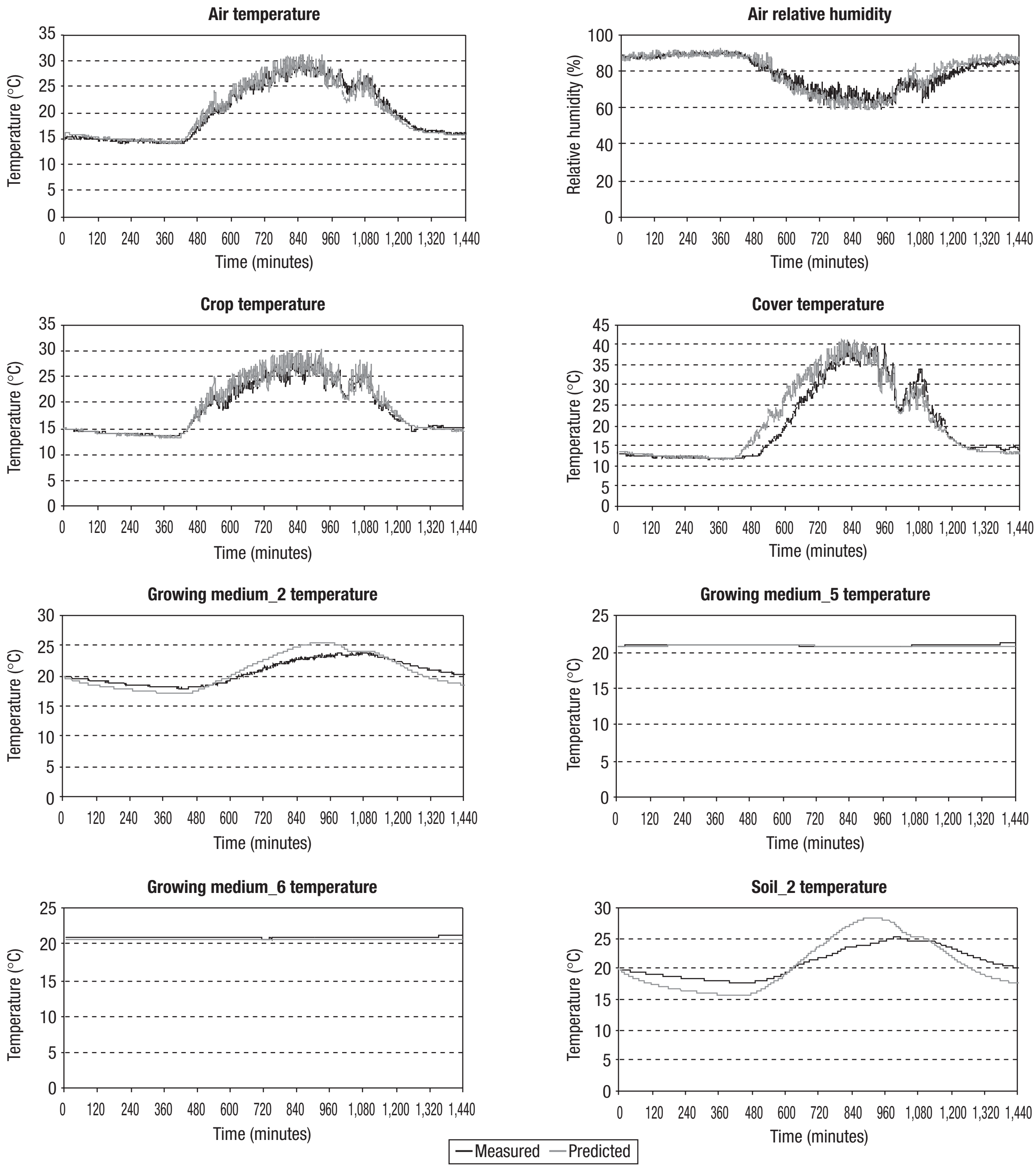

Figure 3. Results of the simulation for 15 May 2000 for the NV greenhouse.

management, but with a tendency to overestimate the effects of large changes in ventilator opening.

Figure 2 shows the performance of the model for 6 July 1998; giving a comparison of the measured and predicted data for some of the process variables over the 24 h. Analysis of Figure 2 shows the reasonable performance of the model over the 24 h simulation period and reveals some differences between the night and day periods. Except for the cover temperature, all the other variables show good agreement during the night, with the maximum differences occurring during the day. The dominant factors in the day energy balance are solar radiation, the transmissivity of the cover material and plant transpiration. In fact, this last factor is very important in determining the crop temperature. There could be two possible explanations, the first is an incorrect sensor reading and the other is that the transpiration was under-estimated by the model, which could be related to the LAI. However, the results are coherent, since the predicted air relative humidity is lower than the measured value for most of the day period. The predicted cover temperature is consistently lower than measured, but with a good performance, since the lines have the same variation over the day, which explains the high determination coefficient (r_a^2=0.99). During the night, the cover heat balance is affected mainly by the sky temperature and the convection heat transfer coefficient. The sky temperature seems to be adequate, which is shown by the good agreement found for the rest of the components, and the convection heat transfer was determined for this specific greenhouse and conditions.

The results of the simulations for 15 May 2000 for the NV and CV greenhouses are presented in Figure 3 and 4, respectively. Ventilation management was achieved by opening the vents at 9:00 h with the same

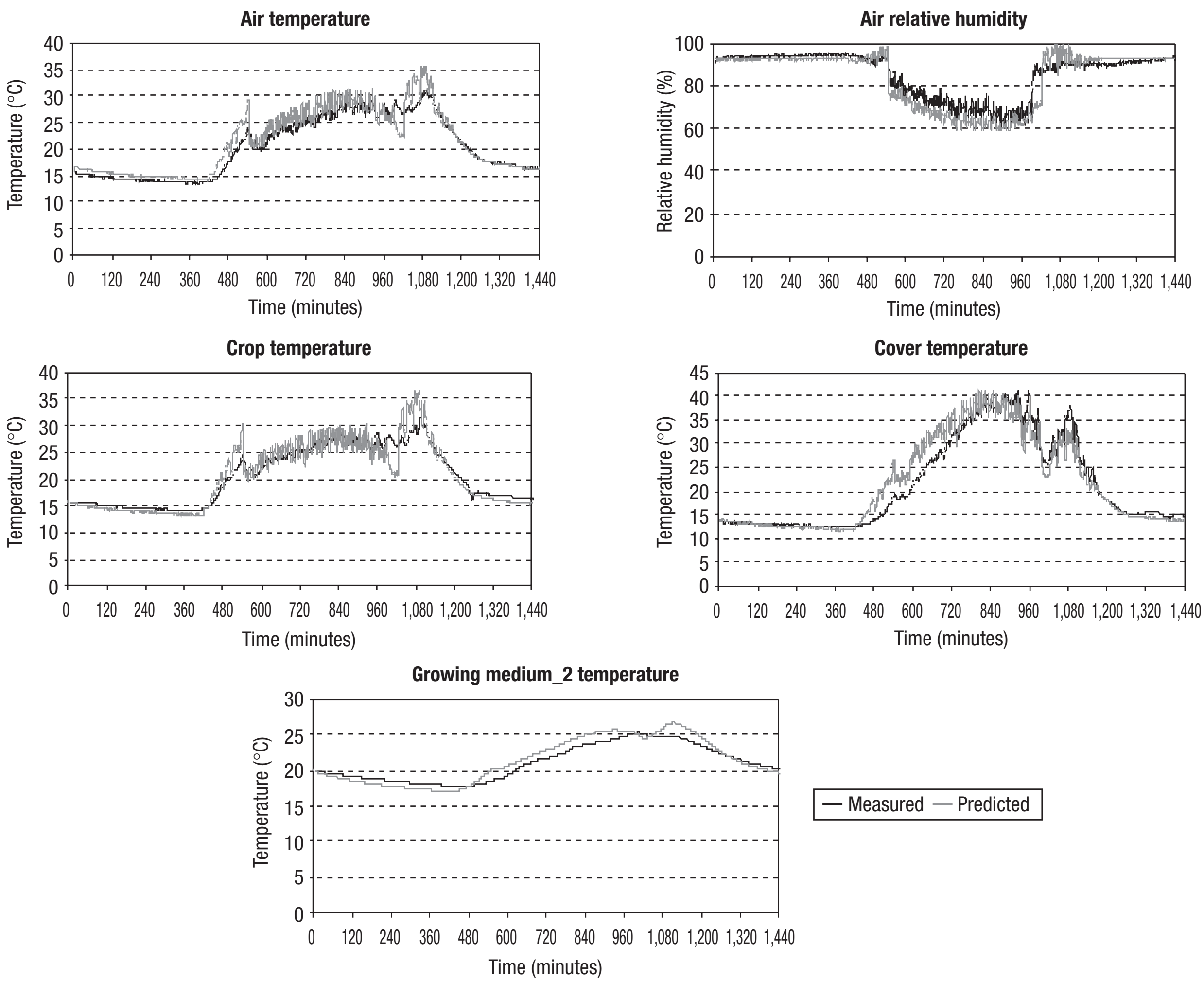

Figure 4. Results of the simulation for 15 May 2000 for the CV greenhouse.

apertures for both greenhouses and by closing totally the vents in the CV greenhouse while in the NV the ventilation area was only reduced, both at 17:00 hours. A general observation of these figures shows that model performance is very good during the whole day for both greenhouses. It is, however, evident there is a stronger model reaction to the opening/closing of the vents in the CV greenhouse. In fact, in this greenhouse after opening the vents we can see an immediate decrease of the air and crop temperatures and also of the air relative humidity, due to the increase in the air exchange rate, which is rapidly compensated by the model readjustment. On the contrary, in the afternoon, after closing the vents, the air and crop temperatures and air relative humidity increase suddenly as the result of the decrease in the air ventilation sensible and latent heat exchange, taking less than 2 h to readjust again. Of course, this reaction to the change in the ventilation areas also occurred in the NV greenhouse, but the model reacts rapidly, as we can see by the agreement between the measured and predicted data at these times. In spite of this, the measured and predicted air and crop temperatures agree very well over the 24 h.

Final considerations

A dynamic climate model was tested, adjusted and validated for the conditions which occurred in unheated tomato greenhouses in a mild winter climate region.

Tests with the original model permitted the identification of the necessary adjustments, which were mainly related with the ventilation and stomatal resistance sub-models, and convection heat transfer coefficients. The new climate model includes sub-models for ventilation and stomatal resistance appropriate for this greenhouse-crop system and new expressions for the convection heat transfer coefficients, which were determined by analysing experimental data.

The model was considered adequate when used with the specific conditions of weather, crop and greenhouses which occurred in our experiments. The validation of the model by comparison of measured and predicted data was realized with independent data recorded in two years of experiments and good agreement between the predicted and measured data was obtained. This model can be used to estimate the greenhouse climate conditions, based on the weather conditions and on the greenhouse-crop system characteristics.

Acknowledgments

The authors which to thank to the Department of Rural Engineering, High Institute of Agronomy, Technical University of Lisbon for the availability of the greenhouses and equipments used during the experimental work.

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