

# Greenhouse crop transpiration simulation from external climate conditions

T. Boulard\*, S. Wang

*I.N.R.A. - Station de Bioclimatologie - Site Agroparc, Domaine Saint Paul, 84914 Avignon Cedex 9, France*

Received 23 April 1999; received in revised form 2 August 1999; accepted 5 August 1999

## Abstract

A new and simple greenhouse crop transpiration model enabling predictions from outdoor conditions is presented and the parameters involved are discussed with respect to different types of greenhouse-crop systems. This transpiration model was validated against experimental data measured in a soil-less tomato crop cultivation in Avignon in summer conditions, when the greenhouse is open, and early spring climatic conditions, when the greenhouse is kept closed and the inside air strongly confined. The evapo-condensation phenomena on the greenhouse cover, particularly important when the greenhouse is closed, are not considered in the water vapour balance. Model estimation improved from spring to summer and comparisons with previous transpiration models have shown that considering outside climate instead of inside climate as a boundary condition implied a deterioration of transpiration model performances especially when greenhouse air is confined. This deterioration is primarily due to simplifications introduced during the model derivation and model performances were satisfactory when the greenhouse air was closely coupled to outdoor conditions. ©2000 Elsevier Science B.V. All rights reserved.

*Keywords:* Greenhouse; Transpiration; Greenhouse climate; Water balance; Ventilation

## 1. Introduction

Previous steps in the development of physically based models of greenhouse crop transpiration considered the water vapour exchange between the protected canopy and the inside air. Crop transpiration is expressed as the sum of a radiative component, proportional to the radiation absorbed by the crop, and an advective term, proportional to the inside air saturation deficit.

Transpiration models with the greenhouse climate as a boundary condition were first developed in the northern regions of Europe and North America for

horticultural crops: tomato (Stanghellini, 1987; Jolliet and Bailey, 1992), cucumber (Yang et al., 1990), lettuce (Pollet et al., 1999). In these northern conditions, the glasshouse is generally poorly ventilated during a large part of the growing season. The boundary layer conductance for glasshouse crops tends to be much smaller than would be expected for similar crops growing outdoors. Thus, glasshouse crops are very strongly decoupled from the outside atmosphere by the presence of the glass, and the heat and the water released at crop surface will accumulate inside the glasshouse. Consequently, the transpiration rate will adjust until it reaches a stable equilibrium transpiration rate dictated by the net radiation received (Jarvis, 1985).

On the contrary, greenhouse crop transpiration in Mediterranean or similar warm conditions is much more dependent on convection. As the ventilation and

\* Corresponding author. Tel.: +33-4-9031-6080;  
fax: +33-4-9089-9810.  
E-mail address: [boulard@avignon.inra.fr](mailto:boulard@avignon.inra.fr) (T. Boulard).

the turbulent mixing are vigorous, the saturation deficit at the leaf surface is closely coupled to the deficit of ambient air, and the latter is directly influenced by the outdoor saturation deficit. The advective contribution represents 43% of the total transpiration for a May–June greenhouse tomato crop in the South of France (Jemaa, 1995) and both radiative and advective components of transpiration must be considered in models (Boulard et al., 1991; Papadakis et al., 1994).

From an operational point of view, the calculation of greenhouse crop transpiration from outside climate is interesting. This is the case in Mediterranean countries where the advective term of transpiration can hardly be estimated because the greenhouses consist of simple shelters, such as tunnels or wooden structures, seldom equipped with inside climate-sensors, which allow calculation of crop transpiration. In addition, when the coupling between inside and outside climatic conditions increases, due to open windows, there are real needs for greenhouse crop transpiration models enabling simulations based on outdoor conditions.

In this paper, we shall derive the basic equations for greenhouse crop transpiration. The parameters involved will be discussed with respect to crop and greenhouse types and the model will be tested against measured data for a tomato crop in both winter and summer conditions.

## 2. Theory

### 2.1. Derivation of crop transpiration with respect to external climatic parameters

The greenhouse-crop system can be considered as a solar collector involving both sensible and latent heat exchanges and its thermal performances can be described in a similar way by the use of a single energy balance equation (Seginer and Albright, 1983; Okano et al., 1985; Boulard and Baille, 1993). The main parameters involved are: the solar efficiency factor ( $\pi$ ) and the overall energy loss coefficient per square metre of greenhouse soil surface ( $K_S$ ,  $\text{W m}^{-2} \text{K}^{-1}$ ).

The greenhouse energy balance can be written

$$\lambda E + H = \pi R_g + Q_h - G - K_S \Delta T \quad (1)$$

where  $E$  is the canopy transpiration ( $\text{kg m}^{-2} \text{s}^{-1}$ ),  $\lambda$  the latent heat of water vaporisation ( $\text{J kg}^{-1}$ ),  $H$  the sensible heat exchange by ventilation ( $\text{W m}^{-2}$ ),  $R_g$  the outside global solar radiation ( $\text{W m}^{-2}$ ),  $Q_h$  the heating flux density ( $\text{W m}^{-2}$ ) provided by the heating system,  $G$  the heat storage or retrieval rate of the greenhouse-soil system ( $\text{W m}^{-2}$ ),  $K_S$  the overall heat transfer coefficient between inside and outside and  $\Delta T$  the air temperature difference between inside and outside (K).

The latent heat exchange due to canopy transpiration can be expressed with respect to the difference of air humidity between indoors and outdoors:

$$\lambda E = K_v \Delta e \quad (2)$$

where  $\Delta e$  is the water vapour pressure gap between the interior and exterior air (Pa) and  $K_v$  is the latent heat transfer coefficient ( $\text{W m}^{-2} \text{Pa}^{-1}$ ).

The sensible heat exchange by ventilation can also be expressed with respect to the difference of air temperature between indoors and outdoors:

$$H = K_H \Delta T \quad (3)$$

where  $\Delta T$  is the temperature gap between interior and exterior air (K) and  $K_H$  the sensible heat transfer coefficient ( $\text{W m}^{-2} \text{K}^{-1}$ ).

Greenhouse crop transpiration can be deduced from the greenhouse available energy ( $\lambda E + H$ ) and from the inside air saturation deficit  $D_i$  (Pa), by means of the Penman–Monteith formula:

$$\lambda E = \frac{\delta(\lambda E + H) + 2L\rho C_p D_i / r_a}{\delta + \gamma(1 + r_s / r_a)} \quad (4)$$

where  $C_p$  and  $\rho$  are the specific heat of air at constant pressure ( $\text{J kg}^{-1} \text{K}^{-1}$ ) and the air density ( $\text{kg m}^{-3}$ ),  $\gamma$  is the psychrometric constant ( $\text{Pa K}^{-1}$ ),  $r_a$  and  $r_s$  are the aerodynamic and stomatal resistances of the leaves ( $\text{s m}^{-1}$ ) and  $L$  is the leaf area index for the whole floor area including pathways.

The water vapour pressure deficit of the interior air ( $D_i$ ) can be expressed as a linear function of the water vapour pressure deficit and temperature of exterior air,  $D_o$  and  $T_o$ :

$$D_i = \delta(T_o)(\Delta T) - \Delta e + D_o \quad (5)$$

where  $\delta(T_o)$  is the slope of the water vapour saturation curve at  $T_o$  ( $\text{Pa K}^{-1}$ ). The above system constitutes

a linear system of five equations with five unknowns ( $\lambda E$ ,  $H$ ,  $D_i$ ,  $\Delta T$  and  $\Delta e$ ) which can be solved analytically. Consequently,  $\lambda E$  can be expressed with respect to the outside climate and greenhouse-crop parameters.

Combining Eqs. (1) and (3) yields

$$\Delta T = \frac{1}{K_H + K_S} (\pi R_g + Q_h - G - \lambda E) \quad (6)$$

By introducing Eq. (2), Eq. (5) becomes

$$D_i = \delta \Delta T - \frac{\lambda E}{K_v} + D_o \quad (7)$$

Combining Eqs. (3) and (4) yields

$$\lambda E = \frac{\delta(\lambda E + K_H \Delta T) + 2L\rho C_p D_i / r_a}{\delta + \gamma(1 + r_s / r_a)} \quad (8)$$

The above simplifications allow us to obtain a simplified system with three equations (Eqs. (6)–(8)) and three unknowns ( $\lambda E$ ,  $D_i$  and  $\Delta T$ ).

Eq. (8) can be simplified as follows:

$$\lambda E = \frac{K_1 K_H \Delta T + K_2 D_i}{1 - K_1} \quad (9)$$

with

$$K_1 = \frac{\delta}{\delta + \gamma(1 + r_s / r_a)} \quad (10)$$

$$K_2 = \frac{2L\rho C_p / r_a}{\delta + \gamma(1 + r_s / r_a)} \quad (11)$$

Combining Eqs. (7) and (9) eliminates  $D_i$ :

$$\lambda E = \frac{(K_1 K_H + K_2 \delta) \Delta T + K_2 D_o}{1 - K_1 + (K_2 / K_v)} \quad (12)$$

$\Delta T$  is removed by combining Eqs. (6) and (12) and the crop transpiration can finally be expressed with respect to external climatic parameters and transfer coefficients:

$$\lambda E = \frac{\pi R_g + Q_h - G + ((K_S + K_H) K_2 D_o) / (K_1 K_H + K_2 \delta)}{1 + ((K_S + K_H)(1 - K_1 + K_2 / K_v)) / (K_1 K_H + K_2 \delta)} \quad (13)$$

## 2.2. Estimation of parameters

The solar heating efficiency of the greenhouse ( $\pi$ ) is a key factor that strongly modulates the influence of

solar radiation (Seginer and Albright, 1983, Boulard and Baille, 1993). It can be deduced from the greenhouse energy balance (1) over 24-hour periods:

$$\sum \lambda E + \sum H = \pi \sum R_g + \sum Q_h - \sum G - K_S \sum \Delta T$$

Assuming that the sum of soil heat storage and retrieval ( $\sum G$ ) is approximately null over a 24-hours period, we get a simple formula enabling the identification of  $\pi$ :

$$\pi = \frac{\sum (\lambda E + H - Q_h + K_S \Delta T)}{\sum R_g} \quad (14)$$

The overall energy loss coefficient can be considered as dependent on external wind speed  $V$  ( $\text{m s}^{-1}$ ) following the simple relation (Bailey and Cotton, 1980):

$$K_S = A + BV \quad (15)$$

where  $A$  and  $B$  depend on the greenhouse design (ratio of the soil surface, on the greenhouse cover:  $S_s/S_c$ ), on the type of the cover material (glass, polyethylene, PVC) and the presence of a single or double cover.

The coefficients for the transfer of sensible and latent heat by ventilation,  $K_H$  and  $K_v$ , are proportional to the ventilation flux,  $\phi_v$  ( $\text{m}^3 \text{s}^{-1}$ ). Ignoring buoyancy forces, the latter can be considered to be linearly dependent on the vent opening area and wind speed (Boulard and Baille, 1995; Kittas et al., 1995):

$$\phi_v = \frac{S_0}{2} C_d C^{0.5} V \quad (16)$$

where  $C$  is a wind related efficiency coefficient,  $C_d$  is an average vent discharge coefficient and  $S_0$  is the vent opening area ( $\text{m}^2$ ).

So, we obtain:

$$K_H = \frac{\rho C_p \phi_v}{A_g} \quad (17)$$

$$K_v = \frac{\lambda \xi \rho \phi_v}{A_g} \quad (18)$$

where  $A_g$  is the greenhouse ground area ( $\text{m}^2$ ),  $\xi$  the conversion factor between the air water vapour content ( $\text{kg}_w \text{kg}_a^{-1}$ ) at standard temperature and the air water vapour pressure (Pa),  $6.25 \times 10^{-6} \text{kg}_w \text{kg}_a^{-1} \text{Pa}^{-1}$ .

The following relation (Murray, 1967) gives the slope of the water vapour saturation curve to the temperature:

$$\delta = \frac{2504000}{(T - 35.86)^2} e^{17.27(T-273.16)/(T-35.86)} \quad (19)$$

According to Avissar et al. (1985), the stomatal resistance can be considered to be dependent on the inside level of global radiation and inside air temperature and humidity based on exponential laws. For greenhouse tomato crops, the effects of radiation on stomatal resistance is the most crucial and obeys the following relation (Boulard et al., 1991):

$$r_s = 200 \left( 1 + \frac{1}{\exp(0.05(\tau R_g - 50))} \right) \quad (20)$$

where  $\tau$ , is the transmittance of the greenhouse cover.

The aerodynamic resistance,  $r_a$ , mainly depends on the aerodynamic regime that prevails in the greenhouse. If we consider that the buoyancy force can be ignored with respect to the wind force,  $r_a$  can be directly expressed with respect to the average interior air speed:

$$r_a = 220 \frac{d^{0.2}}{V_i^{0.8}} \quad (21)$$

where  $d$  is the characteristic length of the leaf (m).  $V_i$ , the mean interior air speed ( $\text{m s}^{-1}$ ), can be considered to be proportional to the ventilation flux  $\phi_v$  divided by  $A_c$  ( $\text{m}^2$ ), the vertical cross-section area perpendicular to the average direction of the inside air flux, in this case the greenhouse axis (Wang et al., 1999):

$$V_i = \frac{\phi_v}{A_c} \quad (22)$$

### 3. Materials and methods

#### 3.1. Greenhouse and experimental set up

The study was carried out from March to June in a climate controlled bi-span plastic-house equipped with both heating and cooling devices. The greenhouse was 32 m long in the north–south direction and consisted of two spans, each of 6.5 m width. The mean height was 4 m. Two vents, each 1.06 m wide, ran the length of the entire greenhouse near the gutters. The ratio of the total vent area to ground area was 0.32. Maximum vent opening angle of the vents was  $58^\circ$ .

Tomato plants, c.v. Rondello, were planted in double rows (density = 2 plants/ $\text{m}^2$ ) in January and grown

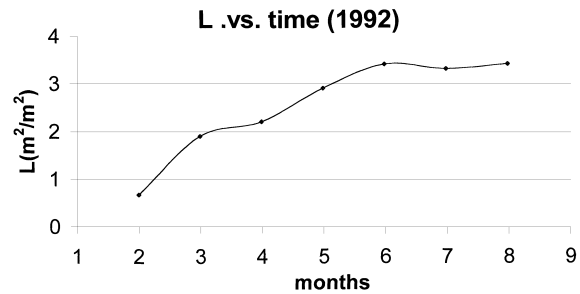


Fig. 1. Tomato crop Leaf Area Index ( $L$ ) as a function of time. February to August 1992.

on rockwool slabs placed on a white plastic mulch. The heating and ventilation set points were approximately 17 and  $22^\circ\text{C}$ , respectively. The leaf area index ( $L$ ) was estimated each month from measurements of leaf dimensions (Jemaa, 1995) and the daily data were interpolated (Fig. 1).

#### 3.2. Climatic and transpiration measurements

Inside and outside climate variables, dry and wet bulb temperatures and global radiation were monitored at hourly time increments, together with the state of the actuators (vent opening) and the heating energy consumption.

Crop transpiration was determined by means of a weighing lysimeter (maximum load 120 kg, precision  $\pm 10$  g) supporting four plants. All the measurements were sensed every minute, averaged on the hourly basis and stored in a data logger. A complete description of the greenhouse and climatic and transpiration measurements can be found in Draoui (1994) and Jemaa (1995).

### 4. Results and discussion

All the forthcoming results were determined using data collected during two successive years: 1991 and 1992. The solar efficiency of the greenhouse,  $\pi$ , was determined using the data from spring 1991 and the transpiration model was validated against the transpiration measurements collected during the spring of 1992. Data from individual ventilation experiments performed over several years, sometimes in an empty greenhouse, enabling extreme environmental

conditions, were also used for the identification of the parameters of the ventilation model (Boulard, 1993).

#### 4.1. Solar efficiency, $\pi$

The daily course of the identified value of  $\pi$  (Eq. (14), with  $K_S = 6 + 0.5V$ ) from 7 April to 4 May is given in Fig. 2. It averaged  $\pi = 0.59$ , to be compared with  $\pi = 0.50$ , found in a 7 m tunnel occupied by a young tomato crop (Sbita et al., 1998), or  $\pi = 0.56$  for a single glazed greenhouse (Garzoli, 1985). The standard mean deviation is equal to 0.05. These variations can be due to simplifications in the heat and mass and ventilation models which will be analysed in Section 4.4, or to errors in the measurement of the involved climatic parameters  $T$ ,  $R_g$ ,  $e$  and  $V$ .

#### 4.2. Crop transpiration

Assuming that  $G$  was negligible with respect to the other terms of the heat balance and using the identified value of solar efficiency ( $\pi = 0.59$ ), the transpiration model was validated with respect to two types of climatic conditions: (i) summer or late spring climatic conditions, when the coupling between the

greenhouse crop and the outside climate was important and (ii) winter or early spring climatic conditions, when the greenhouse was not ventilated and the inside air strongly confined.

Calculated versus measured greenhouse crop transpiration fluxes together with their regression lines and statistical parameters are given on an hourly basis in Figs. 3 and 4 for the periods 1–31 May 1992, and 10–31 March 1992, respectively. Model estimation improved from March to May, as seen by the increase of the slope of the regression line and by the improvement of the correlation coefficient. The standard deviations are similar in March and in May ( $23 \text{ W m}^{-2}$ ) and the slopes of the regression lines are always lower than 1, especially in March, which indicates that the model systematically underestimates the transpiration fluxes.

The hourly courses of measured and computed transpiration fluxes are shown in Figs. 5 and 6 for the May and March periods, respectively. In May, a good fit between measured and simulated data can be observed in both diurnal and nocturnal periods and the precision of the model is similar on sunny days (corresponding to the days with high transpiration fluxes) and overcast days (corresponding to the days with low transpiration fluxes).

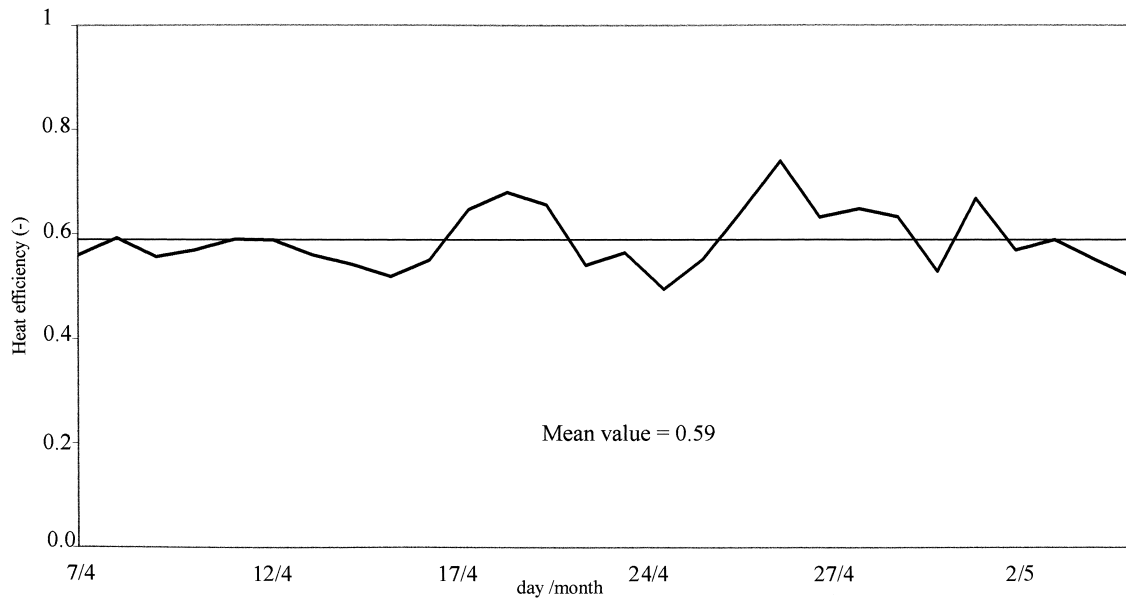


Fig. 2. The greenhouse solar efficiency ( $\pi$ ) as a function of time. 7 April to 4 May 1991.

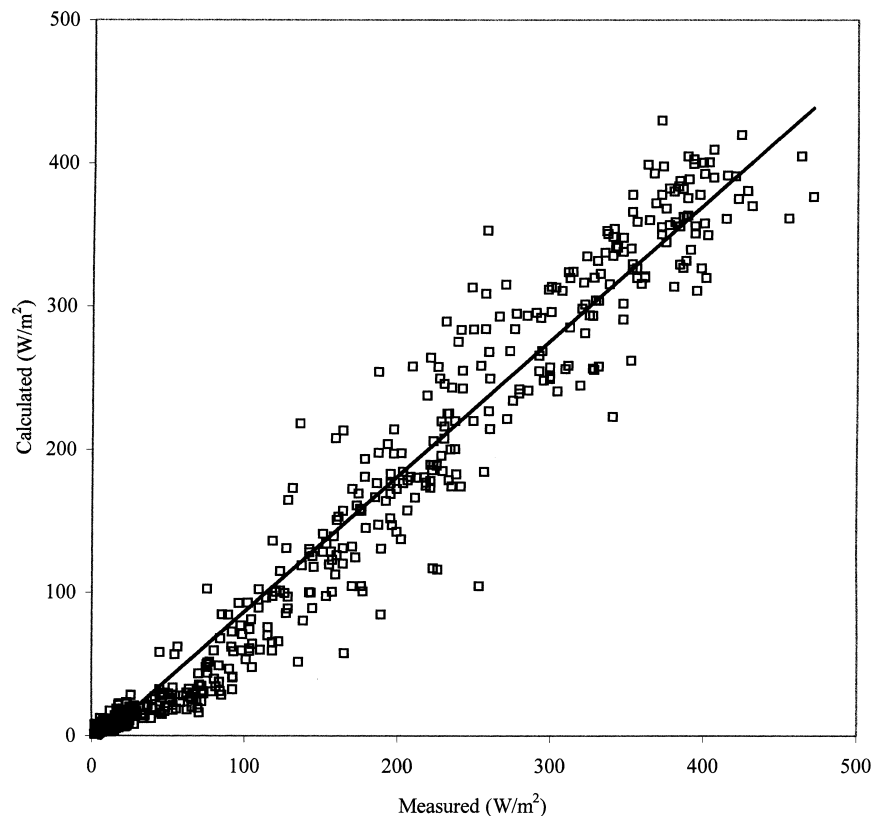


Fig. 3. Calculated ( $\lambda E_{\text{cal}}$ , present transpiration model) versus measured ( $\lambda E_{\text{mes}}$ , lysimeter measurement) values of greenhouse crop transpiration rate.  $\lambda E_{\text{cal}} = 0.95\lambda E_{\text{mes}} + 7.64$ , regression coefficient:  $R^2 = 0.97$ , standard deviation:  $\sigma = 23.29 \text{ W m}^{-2}$ ,  $N = 744$  values, 1–31 May 1992, hourly basis. The precision of the lysimeter measurement was about  $\pm 3.5 \text{ W m}^{-2}$ .

Larger discrepancies are noticed in March during night-time when the greenhouse was closed and when the heating system was systematically activated. A similar deterioration of model performances can also be observed in daytime when the transpiration flux was weak, as was the case during cloudy days (corresponding to the days with low transpiration fluxes).

#### 4.3. Comparison with previous models

Using the same experimental data and the same crop parameters ( $L$ ,  $r_s$ ), this model can also be compared at an hourly time-step with previous greenhouse crop transpiration models based on the Penman–Monteith formula and considering only inside climate (Jemaa, 1995). The regression lines between measured and calculated transpiration fluxes and the associated statis-

tical parameters for the May and March periods are shown in Table 1.

It is clear that considering outside climate instead of inside climate as a boundary condition implies a deterioration of transpiration model performances. However, in May we observed only a slight underestimation and loss of prediction of the model, while in March the underestimation of the transpiration fluxes reached almost 20% and the  $R^2$  decreased by 0.1 with respect to the March value.

#### 4.4. Model limits

The deterioration of the model performances detected in winter and early spring is mainly due to several simplifications introduced during the model derivation.

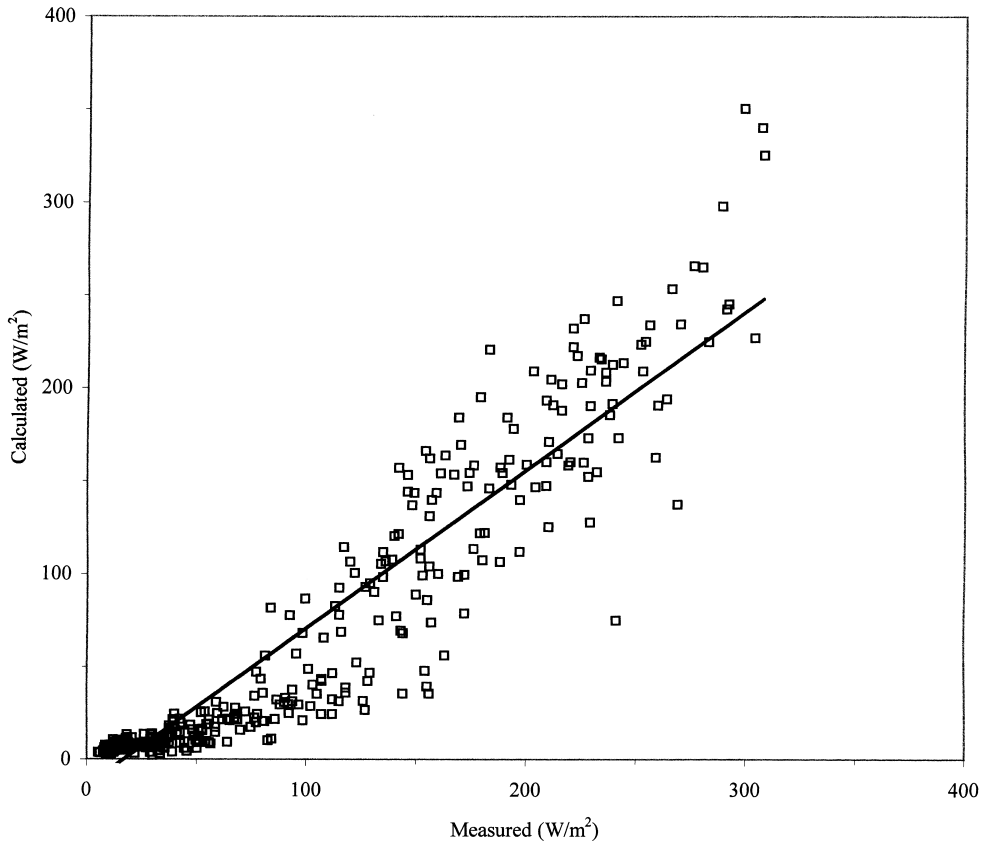


Fig. 4. Calculated ( $\lambda E_{\text{cal}}$ , present transpiration model) versus measured ( $\lambda E_{\text{mes}}$ , lysimeter measurement) values of greenhouse crop transpiration rate.  $\lambda E_{\text{cal}} = 0.85\lambda E_{\text{mes}} + 14.27$ , regression coefficient:  $R^2 = 0.89$ , standard deviation:  $\sigma = 23.39 \text{ W m}^{-2}$ ,  $N = 504$  values. 10–31 March 1992, hourly basis. The precision of the lysimeter measurement was about  $\pm 3.5 \text{ W m}^{-2}$ .

The evapo-condensation phenomena on the greenhouse cover, particularly important when the greenhouse is closed, are not considered in the water vapour balance described by relation (2). Relation (5) allowing for the derivation of the water vapour pressure deficit of inside air ( $D_i$ ) as a linear function of the water vapour pressure deficit and temperature of the exterior air,  $D_o$  and  $T_o$ , is verified only when  $e_s(T_i) - e_s(T_o) \cong \delta(T_o)\Delta T$ , i.e. when  $T_i$  is not too far from  $T_o$ . This is not the case during winter when, as in our experimental conditions, the greenhouse is heated.

These two reasons could explain the majority of the discrepancies, however, other causes, due to the ventilation model, must also be examined.

Linearisation of the model requires a linear relationship describing ventilation. That is why relation (16) neglects the buoyancy forces linked to  $\Delta T$ , though

these forces can be significant, particularly when  $\Delta T$  is high ( $\Delta T > 5^\circ\text{C}$ ) and  $V$  is low ( $V < 1.5 \text{ m s}^{-1}$ ).

No leakage model was considered in our description of the air exchange rate and this can also explain a large part of the differences observed between simulations and measurements at night-time.

All these errors occur when the greenhouse is closed, but their magnitude is not significant because the transpiration fluxes are generally weak at that time. They could also be corrected but this would detract from the simplicity and robustness of the model.

#### 4.5. Model applications

Three major types of applications could be considered for this model: (i) the direct estimation of crop

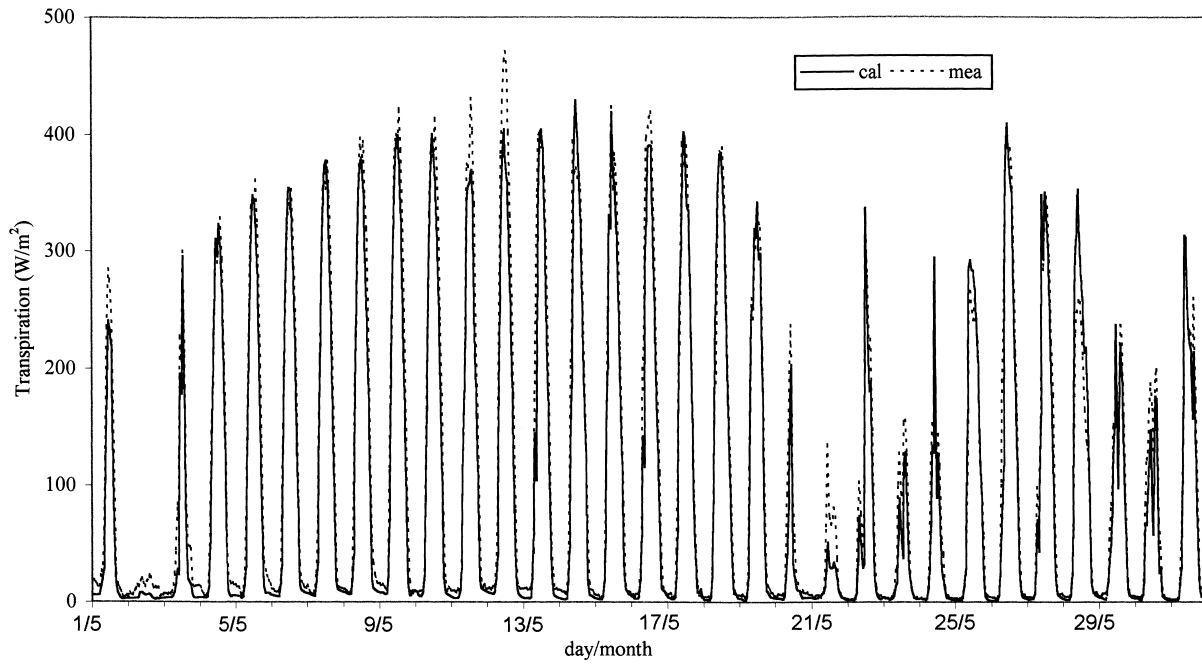


Fig. 5. Time courses of measured (lysimeter measurement) and calculated (present transpiration model) values of tomato crop transpiration rates. May 1992, hourly basis.

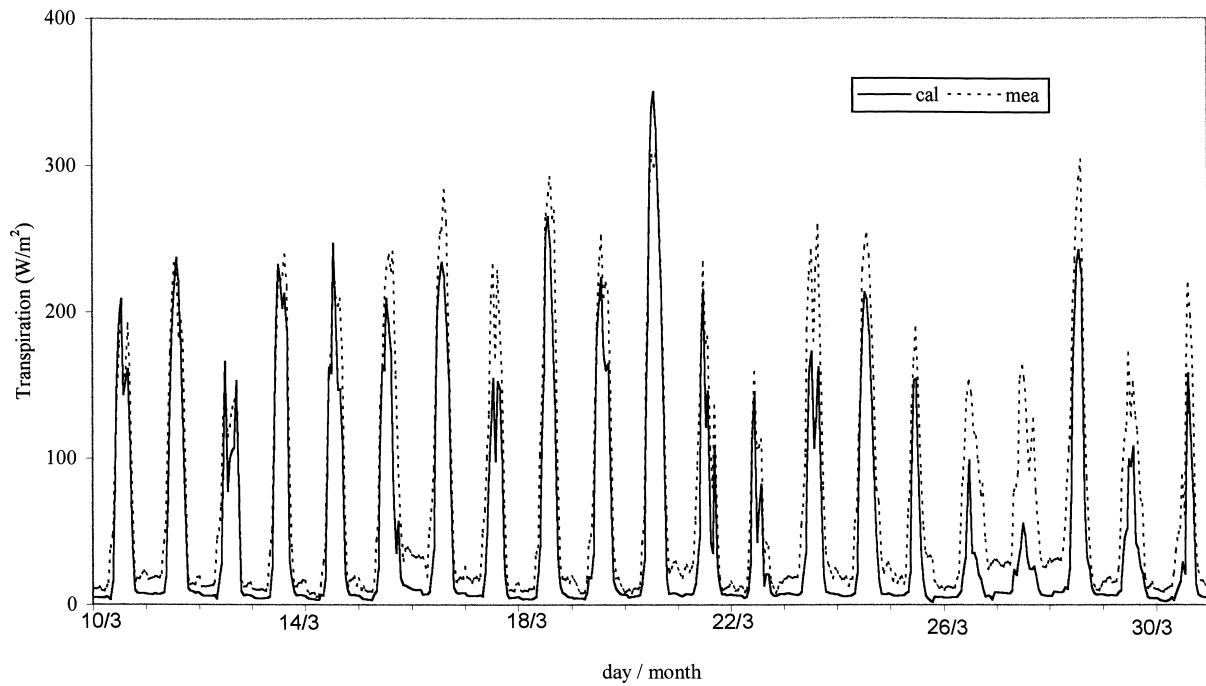


Fig. 6. Time courses of measured (lysimeter measurement) and calculated (present transpiration model) values of tomato crop transpiration rates. March 1992, hourly basis.



Table 1

Comparison of the regression lines and associated statistical parameters between the measured greenhouse crop transpiration ( $\lambda E_{\text{meas}}$ ) and simulations performed by the present model ( $\lambda E_{\text{cal,o}}$ ) and a previous model ( $\lambda E_{\text{cal,i}}$ ) with inside climate as boundary conditions (Jemaa, 1995),  $\sigma$ : standard deviation of the regression line,  $R$ : regression coefficient

Transpiration models	1–31 May 1992; N: 744 points	10–31 March 1992; N: 504 points
PM and inside climate	$\lambda E_{\text{cal,i}} = 1.01\lambda E_{\text{meas}} + 4.45$ , $\sigma = 13 \text{ W m}^{-2}$ , $R^2 = 0.99$	$\lambda E_{\text{cal,i}} = 1.03\lambda E_{\text{meas}} + 4.4$ , $\sigma = 9.2 \text{ W m}^{-2}$ , $R^2 = 0.99$
PM and outside climate	$\lambda E_{\text{cal,o}} = 0.95\lambda E_{\text{meas}} - 7.46$ , $\sigma = 23 \text{ W m}^{-2}$ , $R^2 = 0.97$	$\lambda E_{\text{cal,o}} = 0.85\lambda E_{\text{meas}} - 14.27$ , $\sigma = 23.4 \text{ W m}^{-2}$ , $R^2 = 0.89$

transpiration which has already been thoroughly examined, (ii) the calculations of the greenhouse heat and water vapour balances and (iii) the associated greenhouse inside air temperature and humidity. This latter takes into account relations (2) and (13) which enable deriving inside air humidity  $e_i$  and relations (1), (3) and (13) which compute inside air temperature  $T_i$ . The limits of this approach are the same than the limits of the crop transpiration model. However, in order to implement this specific application, the modelling of the heat balance and particularly the description of the overall solar absorption and the system inertia have to be substantially improved.

This model could then be combined with models of cropping system behaviour (De Tourdonnet, 1998; Seginer et al., 1998) in order, for example, to explore different ways of managing fertilisation and irrigation with respect to outside climate and the control of greenhouse vent opening.

## 5. Conclusions

A new greenhouse crop transpiration model enabling predictions from outdoor conditions is derived and the parameters involved are discussed with respect to the different types of greenhouse-crop systems.

Testing of the model in warm and cold conditions shows that estimations of the simulations improve from March to May and from nocturnal to diurnal periods.

The deterioration of model performances detected in winter and early spring is mainly due to simplifications introduced during model derivation; nevertheless such deterioration mainly occur when the greenhouse is closed and generally when the transpiration fluxes are weak.

Finally it appears that the errors observed when the greenhouse is closed could be corrected, but that such

modifications would detract from the model's simplicity and robustness. It is also shown that this transpiration model is designed to be used with simple shelters when inside conditions are closely coupled to outside ones, as is the case in Mediterranean conditions during most of the year.

In addition to the direct estimation of crop transpiration, this model could also be considered to determine inside air temperature and humidity. It could be combined with models of cropping system behaviour using outside climate as boundary conditions.

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