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Research Paper

A methodology for model-based greenhouse design: Part 1, a greenhouse climate model for a broad range of designs and climates

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With the aim of developing a model-based method to design greenhouses for a broad range of climatic and economic conditions, a greenhouse climate model has been developed and validated. This model describes the effects of the outdoor climate and greenhouse design on the indoor greenhouse climate. For use in a greenhouse design method that focused on the optimisation of a set of design elements, the model should fulfil the following three requirements: 1) predict the temperature, vapour pressure and CO_2 concentration of the greenhouse air, with sufficient accuracy for a wide variety of greenhouse designs under varying climate conditions, 2) include the commonly used greenhouse construction parameters and climate conditioning equipment, and 3) consist of a set of first order differential equations to ensure that it can be combined with a tomato yield model (of a similar structure) and to allow the use of ordinary differential equation solvers. The dynamic model was validated for four different greenhouse designs under three climatic conditions: a temperate marine climate, a Mediterranean climate and a semi-arid climate. For these conditions, the model accurately predicted the greenhouse climate for all four designs without modification of the model parameters (except for one case). In more than 78% of the cases, comparison of simulations and measurements of the indoor climate yielded a relative root mean square error of less than 10%. Given these results, the model is considered to be sufficiently accurate and sufficiently generic to be used for developing a model-based greenhouse design method.

1. Introduction

An enormous variety of protected cultivation systems can be found throughout the world. They range from fully passive "solar greenhouses" with thick energy storage walls as found in China (Sun, Zhang, Wang, Cao, & Gu, 2006) to the high-tech "closed greenhouses" in Western Europe (De Jong, Van De Braak, & Bot, 1993). This variety is due to prevailing local conditions, such as climate, economy, social aspects, availability of resources and legislation.

When the current state of greenhouse design is considered, most studies have focused on optimising the design for a specific location, or considered only a single design parameter (Campen, 2005; Kacira, Sase, & Okushima, 2004;

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Nomenclature

State variables

CO_2	Carbon dioxide concentration, mg m^{-3}
T	Temperature, °C
VP	Vapour pressure, Pa

Flux densities

H	Sensible heat flux density, W m^{-2}
L	Latent heat flux density, W m^{-2}
MC	Mass CO_2-flux density, mg m^{-2} s^{-1}
MV	Mass vapour flux density, kg m^{-2} s^{-1}
R	Far infrared radiation (FIR) flux density, W m^{-2}
R_{NIR}	Near infrared radiation (NIR) flux density, W m^{-2}
R_{PAR}	Photosynthetically active radiation (PAR) flux density, W m^{-2}
R_{Glob}	Global radiation flux density, W m^{-2}

External climate inputs

CO_{2Out}	Outdoor CO_2 concentration, mg m^{-3}
I_{Glob}	The outside global radiation, W m^{-2}
T_{Out}	Outdoor temperature, °C
T_{Sky}	Sky temperature, °C
T_{SoOut}	Soil temperature of outer soil layer, °C
VP_{Out}	Outdoor vapour pressure, Pa
v_{Wind}	Outdoor wind speed, m s^{-1}

Remaining symbol

cap	Capacity of the associated state

Subscripts

Air	Greenhouse air compartment below thermal screen
Blow	Direct air heater
Boil	Boiler
Can	Canopy
Cov	Cover
e	External side
Ext	External CO_2 source
Flr	Floor
Fog	Fogging system
Geo	Geothermal heat
Glob	Global radiation
in	Indoor side
Ind	Industrial source
Mech	Mechanical cooling
Out	Outside air
Pad	Pad and fan system
Pas	Passive heat storage facility
Pipe	Pipe heating system
Sky	Sky
So(j)	The '*j*'th the soil layer
Sun	The sun
Top	Compartment above the thermal screen
ThScr	Thermal screen

Sonneveld, Swinkels, Kempkes, Campen, & Bot, 2006; Zaragoza, Buchholz, Jochum, & Perez-Parra, 2007). Von Elsner et al. (2000) concluded that optimisation of a greenhouse design with respect to local climatic and economic conditions still remains a challenge for the designer. As suggested by Baille (1999), a systematic approach that integrates physical, biological and economical models is the most promising way for strategic decision-making on greenhouse configuration for worldwide climate conditions. However, to the best of our knowledge, a model-based methodology to design protected cultivation systems for the wide variety of conditions that exist around the world is not yet available. According to Van Henten et al. (2006), this design problem can be addressed as a multi-factorial optimisation problem. Research on the design of cold storage facilities (Lukasse, Broeze, & van der Sluis, 2009), elevators and car suspension systems (Fathy, 2003) has shown the feasibility of this approach. Regarding greenhouse design, such an optimisation approach relies on a quantitative trade-off between the economic return of the crop and the costs associated with construction, maintenance and operation of the greenhouse facility. To solve this optimisation problem, we developed a model-based greenhouse design method. This method is able to design greenhouses for a broad range of climatic and economic conditions. The key components of the method are a greenhouse climate model, a tomato yield model, an economic model and an optimisation algorithm as presented in Fig. 1. As a first step, this method focuses on the optimisation of the selection of alternatives to fulfil the following eight design elements: the type of greenhouse structure, the cover type, the outdoor shade screen, the whitewash, the thermal screen, the heating system, the cooling system and the CO_2 enrichment system. This paper contains a description and validation of the greenhouse climate model.

This model describes the effects of outdoor climate and the greenhouse design, including the above-mentioned design elements, on the indoor greenhouse climate. The estimated indoor climate will be used as input for the tomato yield model. For use in a model-based greenhouse design method, the model should fulfil the following three requirements:

1. it should predict the greenhouse climate: temperature, vapour pressure and CO_2 concentration of the air with sufficient accuracy for a wide variety of greenhouse designs under varying climate conditions, without modification of model parameters,
2. it should include the commonly used greenhouse design elements to control the indoor climate, so that it can be used to design greenhouses for worldwide conditions,
3. the model should consist of a set of first order differential equations since it will be combined with a tomato yield model consisting of a set of differential equations and to allow the use of ordinary differential equation solvers. In addition, the right-hand sides must be continuously differentiable to speed up the simulation and to ensure that gradient-based dynamic optimisation algorithms can be applied to the model.

Greenhouse climate models have received considerable attention in the literature in recent decades (Baptista, 2007;

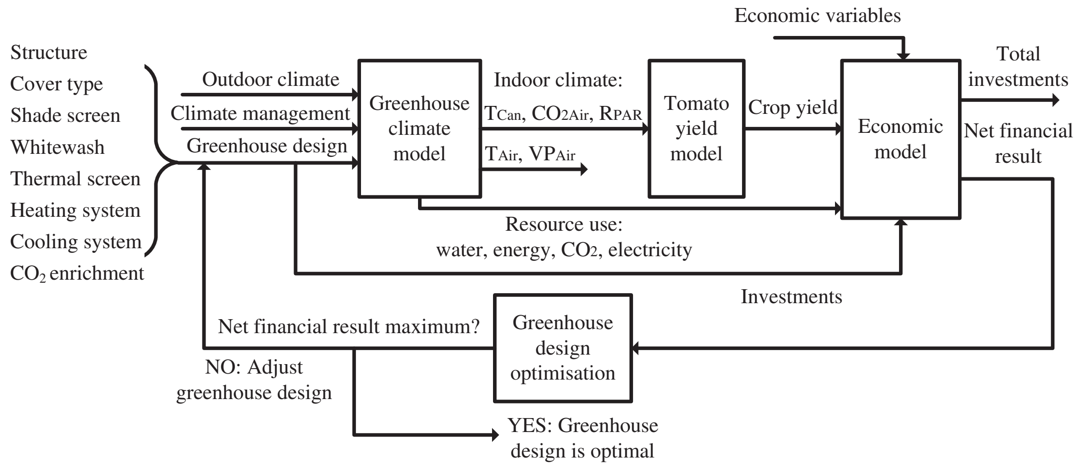

Fig. 1 – An overview of the model-based greenhouse design method. The method focuses on the optimisation of the following eight design elements: the type of greenhouse structure, the cover type, the outdoor shade screen, the whitewash, the thermal screen, the heating system, the cooling system and the CO_2 enrichment system. The key components of the method are a greenhouse climate model, a tomato yield model (Vanthoor et al., 2011), an economic model and an optimisation algorithm. The greenhouse climate model is described in this study.

Bot, 1983; De Halleux, Nijskens, & Deltour, 1991; De Zwart, 1996; Impron, Hemming, & Bot, 2007; Luo et al., 2005; Ooteghem, 2007), but all these authors focused on a single location and a limited and specific set of construction and climate modification elements. Recently, Fitz-Rodríguez et al. (2010) developed a greenhouse environmental model for educational purposes, which was applicable to different design configurations and geographic locations. However, this model was not validated and some model fluxes relevant for the present purpose of greenhouse design were missing. Therefore, by building on the work of Bot (1983) and De Zwart (1996), in our study a more generic greenhouse model was developed and validated for a wide range of greenhouse designs and climates. The following climates were selected to validate the model: a temperate marine climate (northwest part of The Netherlands); a Mediterranean climate, (Sicily, Italy); and a semi-arid climate (Arizona and Texas, USA).

2. Model description

Section 2.1 presents the design elements included in the greenhouse climate model. A concise model description is presented in Section 2.2. A detailed description of the individual mass and energy flows can be found in the electronic appendix.

2.1. *Greenhouse design elements*

Since the focus of the design method is on optimisation of a set of design elements, the selected functions and techniques presented in Fig. 2 were incorporated in the greenhouse climate model. In this model, the greenhouse heating, insulation, shading, cooling, CO_2 enrichment, humidification and de-humidification functions are fulfilled by one or more techniques. For example, the heating function might be fulfilled by the following techniques: a direct air heater, a boiler, an industrial heat source, a geothermal source or a passive buffer.

For the development of a model-based design method, these techniques are considered to be sufficiently generic for a wide range of locations all over the world. Specific local solutions for energy production, energy conversion or climate modification, such as co-generation of heat and electricity, artificial photosynthetic lighting, an active heat buffer, a heat pump and a solar heat collector, lie outside the scope of this study.

2.2. *Model overview and state variables*

2.2.1. *Notational conventions*

All the state variables, fluxes, inputs, superscripts and subscripts are listed in the Nomenclature. Following the notational conventions of De Zwart (1996), the state variables of the model are denoted by names with capital letters followed by one subscript, e.g. T_{Air}. The model fluxes start with a capital letter and are followed by two subscripts. The first subscript represents the source of the flux and the second subscript represents the destination of the flux, e.g. H_{CanAir}. The radiation fluxes start with a capital letter R followed with the type of radiation and then two subscripts to represent the source and sink of the specific radiation, i.e. R_{PAR_SunCan}.

2.2.2. *Model overview and assumptions*

An overview of the state variables and the energy and mass fluxes of the greenhouse model are shown in Fig. 2. The model was based on the following assumptions: 1) the greenhouse air is considered to be a "perfectly stirred tank", which means that there are no spatial differences in temperature, vapour pressure and the CO_2 concentration; therefore, all the model fluxes were described per m^2 of greenhouse floor; 2) to describe the effect of the thermal screen on the indoor climate, the greenhouse air was divided into two compartments: one below and one above the thermal screen.

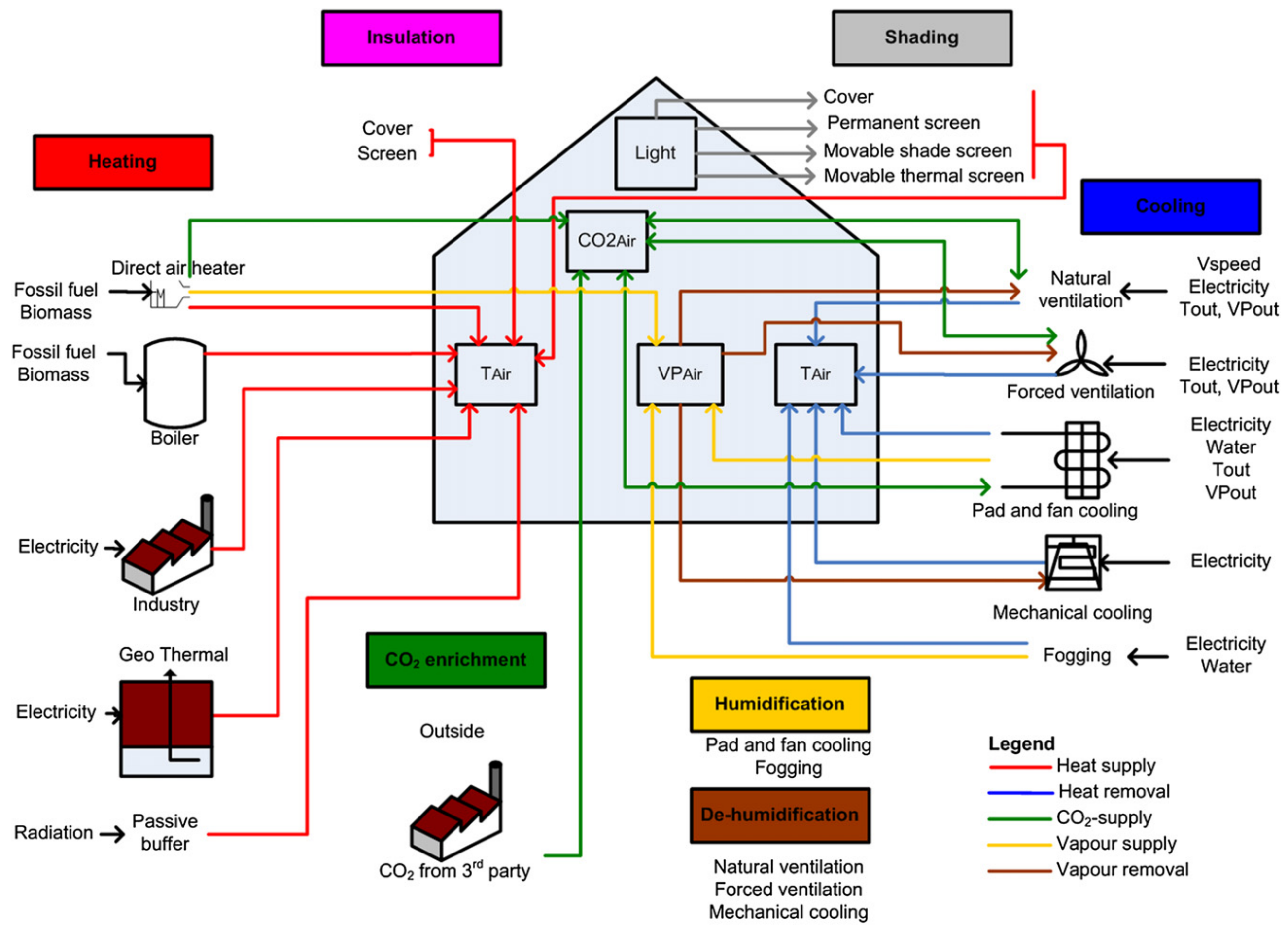

Fig. 2 – Selected functions (coloured boxes), and design elements (text blocks and pictures below the accompanying functions), needed for the greenhouse design method to manage the greenhouse climate (transparent boxes inside the greenhouse). The coloured arrows represent the various energy and mass fluxes (legend at the bottom right). (For interpretation of the colour citation in this figure caption, kindly refer to the online version of this article.)

This model was based on the greenhouse climate modelling study of De Zwart (1996). For the current purpose of greenhouse design, extra model elements were added and some model parts were simplified. The following model elements were implemented: the design elements presented in Fig. 2; a lumped cover description to combine the impact of different cover layers on indoor climate; the internal and external cover temperatures are state variables of the model to describe the impact of cover insulation on indoor climate; a description of the far infrared radiation (FIR) transmission through the cover, which is needed for films that partially transmit FIR; a description of both roof and side ventilation; a description of the impact of insect screens on ventilation rate; and a description of the near infrared radiation (NIR) absorption of both canopy and floor, which depend on the optical properties of the cover and floor.

Since optimisation of the properties of the greenhouse structure i.e. dimensions of the greenhouse, roof slope and orientation and location of the vents, exceeded the purpose of our design method, the model was simplified by making no distinction between diffuse and direct solar radiation and by assuming that the transmission coefficient of the greenhouse cover did not depend on solar angle.

Because of space limitations, the model fluxes are presented in detail in the electronic appendix. A brief description of some relevant fluxes is given here. Assuming a non-limiting irrigation strategy, the transpiration rate of a tomato crop was determined based on the transpiration and stomata model of Stanghellini (1987). The CO_2 fluxes caused by canopy activity, i.e. photosynthesis rate, maintenance and growth respiration, were described by Vanthoor, De Visser, Stanghellini, and Van Henten (2011). The ventilation rate function was based on the equations of Boulard and Baille (1995) and Kittas, Boulard, and Papadakis (1997).

2.2.3. *State variables of the model*

The state variables of the model are all described by differential equations. The derivatives of the state variables to time are indicated by a dot above the state symbol.

2.2.3.1. *Temperature of different greenhouse components.*

Canopy temperature T_{Can} is described by:

$$cap_{Can}\dot{T}_{Can} = R_{PAR\_SunCan} + R_{NIR\_SunCan} + R_{PipeCan} - H_{CanAir} - L_{CanAir} - R_{CanCov,in} - R_{CanFlr} - R_{CanSky} - R_{CanThScr} \quad [\mathrm{W\,m^{-2}}] \quad (1)$$

where cap_{Can} is the heat capacity of the canopy, R_{PAR_SunCan} is the PAR absorbed by the canopy, R_{NIR_SunCan} is the NIR absorbed by the canopy. FIR is exchanged between the canopy and surrounding elements i.e. the heating pipes $R_{PipeCan}$, the internal cover layer $R_{CanCov,in}$, the floor R_{CanFlr}, the sky R_{CanSky}, and the thermal screen $R_{CanThScr}$. H_{CanAir} is the sensible heat exchange between canopy and greenhouse air and L_{CanAir} is the latent heat flux caused by transpiration.

Greenhouse air temperature T_{Air} is described by:

$$cap_{Air}\dot{T}_{Air} = H_{CanAir} + H_{PadAir} + H_{MechAir} + H_{PipeAir} + H_{PasAir} + H_{BlowAir} + R_{Glob\_SunAir} - H_{AirFlr} - H_{AirThScr} - H_{AirOut} - H_{AirTop} - H_{AirOut\_Pad} - L_{AirFog} \left[\mathrm{W\ m^{-2}}\right] \quad (2)$$

where cap_{Air} is the heat capacity of the greenhouse air. Sensible heat is exchanged between the greenhouse air and the surrounding elements i.e. the canopy H_{CanAir}, the outlet air of a cooling pad H_{PadAir}, the mechanical cooling system $H_{MechAir}$, the heating pipes $H_{PipeAir}$, the passive energy buffer H_{PasAir}, the direct air heater $H_{BlowAir}$, the floor H_{AirFlr}, the thermal screen $H_{AirThScr}$, the outdoor air H_{AirOut}, the air of the top compartment which is located above the thermal screen H_{AirTop}, and the outdoor air due to the air exchange caused by the pad and fan system H_{AirOut_Pad}. R_{Glob_SunAir} is the global radiation which is absorbed by the construction elements and which is released to the air and L_{AirFog} is the latent heat needed to evaporate the water droplets added by a fogging system.

The floor layer is the first layer of the greenhouse underground and its temperature T_{Flr} is described by:

$$cap_{Flr}\dot{T}_{Flr} = H_{AirFlr} + R_{PAR\_SunFlr} + R_{NIR\_SunFlr} + R_{CanFlr} + R_{PipeFlr} - H_{FlrSo1} - R_{FlrCov,in} - R_{FlrSky} - R_{FlrThScr} \quad \left[\mathrm{W\ m^{-2}}\right] \quad (3)$$

where cap_{Flr} is the heat capacity of the floor; R_{PAR_SunFlr} is the PAR absorbed by the floor; R_{NIR_SunFlr} is the NIR absorbed by the floor; $R_{PipeFlr}$, $R_{FlrCov,in}$, R_{FlrSky} and $R_{FlrThScr}$ are the FIR fluxes between the floor and heating pipes, internal cover layer, sky and thermal screen respectively; and H_{FlrSo1} is the sensible heat flux from the floor to soil layer 1.

Because of the high thermal capacity, the soil was divided into five layers with an increasing thickness with increasing depth. The soil temperature $T_{So(j)}$ of layer 'j' is described by:

$$cap_{So(j)}T_{So(j)} = H_{So(j-1)So(j)} - H_{So(j)So(j+1)} \quad j = 1, 2\ldots5 \quad \left[\mathrm{W\ m^{-2}}\right] \quad (4)$$

where $cap_{So(j)}$ is the heat capacity of each soil layer, $H_{So(j-1)So(j)}$ is the conductive heat flux from layer '$j-1$' to 'j' and $H_{So(j)So(j+1)}$ is the conductive heat flux from layer 'j' to '$j+1$'. For the first soil layer, $H_{So(j-1)So(j)}$ is equivalent to H_{FlrSo1} and for the last soil layer, $H_{So(j)So(j+1)}$ is equivalent to the conductive heat flux from the 5th soil layer to the external soil temperature $H_{So5SoOut}$.

Temperature of the thermal screen T_{ThScr} is described by:

$$cap_{ThScr}\dot{T}_{ThScr} = H_{AirThScr} + L_{AirThScr} + R_{CanThScr} + R_{FlrThScr} + R_{PipeThScr} - H_{ThScrTop} - R_{ThScrCov,in} - R_{ThScrSky} \quad \left[\mathrm{W\ m^{-2}}\right] \quad (4)$$

where cap_{ThScr} is the heat capacity of the thermal screen; $L_{AirThScr}$ is the latent heat flux caused by condensation on the thermal screen; $R_{PipeThScr}$, $R_{ThScrCov,in}$ and $R_{ThScrSky}$ are the FIR fluxes between the thermal screen and the heating pipes, internal cover layer and sky respectively; and $H_{ThScrTop}$ is the heat exchange between the thermal screen and the top compartment air.

The air temperature of the compartment above the thermal screen T_{Top}, in this study denoted as the 'top compartment', is described by:

$$cap_{Top}\dot{T}_{Top} = H_{ThScrTop} + H_{AirTop} - H_{TopCov,in} - H_{TopOut} \quad \left[\mathrm{W\ m^{-2}}\right] \quad (6)$$

where cap_{Top} is the heat capacity of the top compartment air, $H_{TopCov,in}$ is the heat exchange between the top compartment air and the internal cover layer and H_{TopOut} is the heat exchange between the top compartment and the outside air.

The thermal heat conductivity of the greenhouse cover is a greenhouse design parameter which can induce a significant temperature gradient across the cover. Therefore, both the internal cover temperature and external cover temperature have been modelled. Assuming that the heat capacity of the internal and external cover layer each constitute 10% of the heat capacity of the total cover construction, and assuming that conduction of energy is the dominant mode of energy transport between the internal and the external cover, the internal cover temperature $T_{Cov,in}$ and external cover temperature $T_{Cov,e}$ are described by:

$$cap_{Cov,in}\dot{T}_{Cov,in} = H_{TopCov,in} + L_{TopCov,in} + R_{CanCov,in} + R_{FlrCov,in} + R_{PipeCov,in} + R_{ThScrCov,in} - H_{Cov,inCov,e} \quad \left[\mathrm{W\ m^{-2}}\right] \quad (7)$$

$$cap_{Cov,e}\dot{T}_{Cov,e} = R_{Glob\_SunCov} + H_{Cov,inCov,e} - H_{Cov,eOut} - R_{Cov,eSky} \quad \left[\mathrm{W\ m^{-2}}\right] \quad (8)$$

where $cap_{Cov,in}$ and $cap_{Cov,e}$ are the heat capacities of the internal and external cover layer respectively, $L_{TopCov,in}$ is the latent heat flux caused by condensation on the greenhouse cover, $R_{PipeCov,in}$ is the FIR exchange between the heating pipes and internal cover layer, $H_{Cov,inCov,e}$ is the heat flux between the internal and external cover layer, R_{Glob_SunCov} is the absorbed global solar radiation by the cover, $H_{Cov,eOut}$ is the sensible heat flux from the external cover layer to the outside air and $R_{Cov,eSky}$ is the FIR exchange between the cover and the sky.

In this model, besides using a direct air heater, heat energy can be added to the greenhouse air using hot water heating pipes (Fig. 3). The surface temperature of the heating pipe system T_{Pipe} is described by:

$$cap_{Pipe}\dot{T}_{Pipe} = H_{BoilPipe} + H_{IndPipe} + H_{GeoPipe} - R_{PipeSky} - R_{PipeCov,in} - R_{PipeCan} - R_{PipeFlr} - R_{PipeThScr} - H_{PipeAir} \quad \left[\mathrm{W\ m^{-2}}\right] \quad (9)$$

where cap_{Pipe} is the heat capacity of the heating pipes, $H_{BoilPipe}$ is the boiler heat flux to the pipes, $H_{IndPipe}$ is the industrial heat flux to the pipes, $H_{GeoPipe}$ is the geothermal heat flux to the pipes and $R_{PipeSky}$, is the FIR exchange between the pipes and sky.

2.2.3.2. *Vapour pressure of the greenhouse air and the air in the top compartment*. The vapour pressure of the greenhouse air VP_{Air} is described by:

$$cap_{VP_{Air}}\dot{VP}_{Air} = MV_{CanAir} + MV_{PadAir} + MV_{FogAir} + MV_{BlowAir} - MV_{AirThScr} - MV_{AirTop} - MV_{AirOut} - MV_{AirOut\_Pad} - MV_{AirMech} \quad \left[\mathrm{kg\ m^{-2}\ s^{-1}}\right] \quad (10)$$

where cap_{VPAir} is the capacity of the air to store water vapour. Vapour is exchanged between the air and surrounding elements i.e. the canopy MV_{CanAir}, the outlet air of the pad MV_{PadAir}, the fogging system MV_{FogAir}, the direct air heater

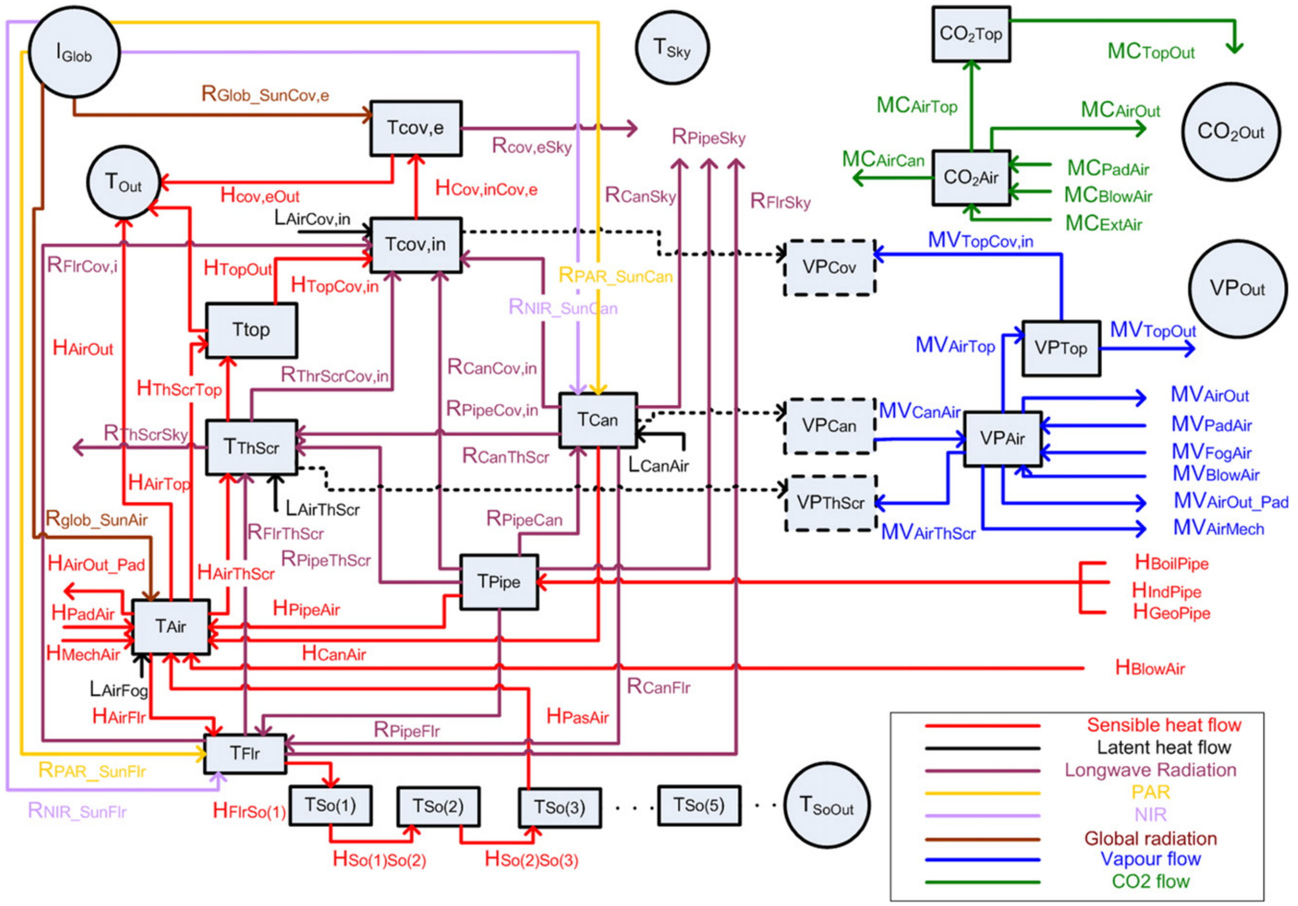

Fig. 3 – Overview of the state variables (blocks), semi-state variables (dotted blocks), external climate inputs (circles) and fluxes (arrows) of the greenhouse model. Coloured arrows represent the various energy and mass fluxes (legend at the bottom right).Abbreviations and their definitions are listed in the Nomenclature, and the underlying equations are presented in Section 2.2.3. (For interpretation of the colour citation in this figure caption, kindly refer to the online version of this article.)

$MV_{BlowAir}$, the thermal screen $MV_{AirThScr}$, the top compartment air MV_{AirTop}, the outdoor air MV_{AirOut}, the outdoor air due to the air exchange caused by the pad and fan system MV_{AirOut_Pad}, and the mechanical cooling system $MV_{AirMech}$.

The vapour pressure of the air in the top compartment VP_{Top} is described by:

$$cap_{VP_{Top}} \dot{V}P_{Top} = MV_{AirTop} - MV_{TopCov,in} - MV_{TopOut} \quad [\mathrm{kg\ m^{-2}\ s^{-1}}] \qquad (11)$$

where $cap_{VP_{Top}}$ is the capacity of the top compartment to store water vapour, $MV_{TopCov,in}$ is the vapour exchange between the top compartment and the internal cover layer and MV_{TopOut} is the vapour exchange between the top compartment and the outside air.

2.2.3.3. CO_2 concentration of the greenhouse air and the air in the top compartment. The greenhouse air CO_2 concentration CO_{2Air} is described by:

$$cap_{CO_{2\ Air}} \dot{C}O_{2\ Air} = MC_{BlowAir} + MC_{ExtAir} + MC_{PadAir} - MC_{AirCan} - MC_{AirTop} - MC_{AirOut} \quad [\mathrm{mg\ m^{-2}\ s^{-1}}] \qquad (12)$$

where $cap_{CO_{2\ Air}}$ is the capacity of the air to store CO_2. Carbon dioxide is exchanged between the greenhouse air and surrounding elements i.e. the direct air heater $MC_{BlowAir}$, the external CO_2 source MC_{ExtAir}, the pad and fan system MC_{PadAir}, the top compartment air MC_{AirTop} and the outdoor air MC_{AirOut}. MC_{AirCan} is the CO_2 flux between the greenhouse air and the canopy as described by Vanthoor et al. (2011).

The CO_2 concentration of the top compartment air CO_{2Top} is described by:

$$cap_{CO_{2\ Top}} \dot{C}O_{2\ Top} = MC_{AirTop} - MC_{TopOut} \quad [\mathrm{mg\ m^{-2}\ s^{-1}}] \qquad (13)$$

where $cap_{CO_{2\ Top}}$ is the capacity of the top compartment air to store CO_2, MC_{TopOut} is the CO_2 exchange between the top compartment air and the outside air.

3. Model validation

The model could be used for model-based greenhouse design if it is able to predict the temperature, vapour pressure and CO_2 concentration of the air with sufficient accuracy for a wide range of greenhouse designs under varying climate conditions. Therefore, four greenhouse designs located in different climate regions were selected to validate the model. The model equations were solved with a stiff ODE solver (ode15s) of Matlab™

(Release 14; The MathWorks Inc., Natick, MA, USA). Measured data of outdoor climate conditions and settings of control valves were used as model inputs. A quantitative criterion was defined to evaluate the model performance.

3.1. Greenhouse design overview

The four greenhouse designs were located in three climatic regions: a temperate marine climate, northwest Netherlands; a Mediterranean climate, Sicily, Italy; and a semi-arid climate, Texas and Arizona, USA. The general details of the individual greenhouses, i.e. location, greenhouse characteristics and climate modification techniques, are listed in Table 1. The presented design elements cover the entire range of functions as listed in Fig. 2: cooling, heating, CO_2 enrichment, insulating, shading, humidification and de-humidification. A detailed overview of the parameters belonging to these design elements, i.e. physical properties to describe the greenhouse structure; ventilation characteristics; cover; whitewash; thermal screen; floor; soil and the capacities of the active climate modification techniques, can be found in the electronic appendix. In all four greenhouses tomatoes were grown. The validation periods of the associated greenhouse designs and the leaf area index (LAI) during validation are shown in Table 2.

3.2. Climate data collection

The climate data of the commercial greenhouses, i.e. Sicily, The Netherlands and Texas, were obtained from weather stations (I_{Glob}, T_{Out}, RH_{Out}, and V_{Wind}) and measurement boxes (T_{Air}, RH_{Air} and CO_{2Air} if available), and these data were recorded by the central climate computer. The climate data of the pad and fan-cooled greenhouse in Arizona were obtained from a commercial weather station (T_{Out}, RH_{Out}, and V_{Wind}), pyranometers (I_{Glob}), thermocouples (T_{Air}) and relative humidity sensors (RH_{Air}). These climate data were recorded using a data logger.

The vapour pressures of the greenhouse air (VP_{Air}) and outside air (VP_{Out}) for all locations were calculated from their psychrometric relationship to the air temperature and air relative humidity. For the missing outdoor climate variables: the outdoor CO_2 concentration (CO_{2Out}) was assumed to be constant at 668 mg m^{-3} (370 ppm); the sky temperature (T_{Sky}) and the temperature of the outer soil layer (T_{SoOut}) were estimated using the equations presented in the electronic appendix.

The energy flow into the heating pipes for the greenhouses located in the Netherlands and in Texas was not measured. For these validation cases, the measured pipe temperature was used as an input of the model. The CO_2 injection rate and/or CO_2 concentration of the greenhouse air were measured in the greenhouse in Sicily throughout the year and during the summer in the greenhouse in The Netherlands. Therefore, the CO_2 concentration was only validated for these two cases.

3.3. Outdoor climate comparison

For all four locations, Table 2 lists the average values and standard deviations of the global radiation and the outdoor temperature, humidity and wind speed during the validation

Table 1 – Greenhouse characteristics and climate modification techniques used in the four greenhouses located in Sicily, The Netherlands, and Texas and Arizona, USA. Crosses denote the installed equipment for which data was used during the validation. Circles denote equipment that was installed, but for which no data was available.

Location	Sicily, Italy	Northwest part of The Netherlands	Texas, USA	Arizona, USA[a]
Geographical coordinates	36°57′N, 14°26′E	53°12′N, 5°29′E	30°21′N, 104°00′W	32°16′N, 110°56′W
Elevation (m above sea level)	104	0	1470	715
Greenhouse characteristics				
Greenhouse type	Arch shape multi-tunnel	Venlo-type	Venlo-type	Arch-shaped single tunnel
Cover type	A double inflated PE layer	A single glass layer	A single glass layer	Polycarbonate sidewalls and an inflated double PE layer
Floor area (m^2)	1.3×10^4	1.4×10^4	7.8×10^4	278
Natural ventilation characteristics	Continuous roof ventilation on one side of each span, covered with insect netting	Ventilation windows on both wind and leeside of the roof	Ventilation windows on both wind and leeside of the roof	Ventilation windows were closed
Climate modification techniques				
Pad and fan cooling				X
Pipe heating		X	X	
CO_2 enrichment		X	O	
Movable thermal screen		X	X	
Movable shade screen			X	X
Whitewash	X[b]		X[c]	

a See Sabeh et al. (2006) for details about the pad and fan-cooled greenhouse design.
b Whitewash was only applied to the greenhouse in the first validation period.
c Whitewash was only applied to the greenhouse in the summer period.

Table 2 – Averages of the outdoor climate conditions for the greenhouses located in Sicily, The Netherlands and Texas and Arizona, USA. Numbers between the brackets represent the standard deviations. An ANOVA revealed that the outdoor climate differed considerably between the first three location because for all outdoor climate variables *Fprob* < 0.001. For the pad and fan-cooled greenhouse in Arizona, the model was validated for different ventilation fluxes applied to the greenhouse between 8.00 and 17.00 h for a sunny day in May 2005.

Location	DOY	Ventilation flux of pad and fan cooling system ($m^3\ m^{-2}\ s^{-1}$)	LAI ($m^2\ m^{-2}$)	I_{Glob_sum} ($MJ\ m^{-2}\ day^{-1}$)	T_{Out} (°C)	VP_{Out} (kPa)	RH_{Out} (%)	V_{Speed} ($m\ s^{-1}$)
Sicily, Italy	267–272	–	1.5	11.6 (2.5)	22.5 (3.4)	2.1 (0.2)	79 (12)	2.5 (2.7)
Sicily, Italy	293–298	–	2.5	8.5 (1.7)	15.2 (3.4)	1.2 (0.3)	69 (13)	2.9 (2.9)
The Netherlands	38–43	–	2.0	6.5 (1.9)	5.9 (2.7)	0.7 (0.1)	80 (11)	2.4 (1.0)
The Netherlands	200–205	–	3.0	15.5 (3.0)	15.2 (1.5)	1.5 (0.2)	85 (9.0)	4.6 (1.4)
Texas, USA	3–8	–	2.5	10.1 (5.9)	5.4 (5.6)	0.6 (0.1)	66 (25)	3.5 (2.8)
Texas, USA	157–162	–	2.0	25.5 (2.5)	23.9 (5.4)	1.3 (0.5)	46 (24)	3.5 (2.4)
Arizona, USA	139	0.016	2.5	25.2	34.2 (2.8)	0.7 (0.0)	13 (2.3)	3.4 (1.2)
Arizona, USA	151	0.034	2.5	26.3	34.2 (3.2)	0.5 (0.0)	9 (2.1)	1.8 (0.9)
Arizona, USA	131	0.047	2.5	24.3	33.5 (3.1)	0.5 (0.1)	10 (3.3)	1.9 (0.9)
Arizona, USA	132	0.060	2.5	23.8	33.5 (2.9)	0.5 (0.0)	10 (2.2)	2.3 (1.1)

experiments. An analysis of variance (ANOVA) using GenStat (Release 12.1 of VSN International Ltd, Hemel Hempstead, UK) revealed that the outdoor climate differed significantly amongst the first three locations, because for all outdoor climate variables *Fprob* < 0.001. For the Arizona location, no ANOVA was performed because the time series of this location were not equal to the other three time series. However, the high ambient temperatures in Arizona ensured that these climate data sets differed from the climate data sets at the other locations.

3.4. *Determination of model performance*

Model performance was evaluated in quantitative terms using the relative root mean square error (RRMSE) according to Kobayashi and Salam (2000):

$$\mathrm{RRMSE} = \frac{100}{\bar{y}_{Data}}\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(y_{Mod,i} - y_{Data,i}\right)^2} \quad [\%] \tag{14}$$

where $\bar{y}_{Data}$ is the mean of measured data over the total time span, n is the number of measurements, $y_{Mod,i}$ is the simulated climate value at time instant '*i*' and $y_{Data,i}$ is the measured climate value at time instant '*i*'. For developing the methodology of optimal greenhouse design, it was assumed that an RRMSE of 10% or less would be sufficient. As demonstrated by Baptista (2007), the performance of most greenhouse climate models is around this value.

4. Results

4.1. *A passive multi-tunnel greenhouse in Sicily, Italy*

The model correctly predicted the temperature (Fig. 4a,b) and the vapour pressure (Fig. 4c,d) for a cold and a hot period in the 'low-tech' greenhouse in Sicily. The CO_2 concentration of the greenhouse air was predicted with fair accuracy (Fig. 4e,f). Although the simulated CO_2 trend was in agreement with the measurements, especially at night, the absolute predicted CO_2 concentrations differed from the measured CO_2 concentrations.

4.2. *A climate-controlled greenhouse in The Netherlands*

The model correctly predicted the temperature (Fig. 5a,b) and the vapour pressure (Fig. 5c,d) during the winter and summer period in The Netherlands, even with large differences between indoor and outdoor climate. The CO_2 concentration of the greenhouse air was correctly predicted during the summer period (Fig. 5e).

The simulated temperature (Fig. 5a) and vapour pressure (Fig. 5c) were overestimated only at day-of-the-year (DOY) 42 during the daytime. This was caused by an underestimated simulated ventilation rate. This underestimation took place because the effect of the vapour pressure difference on ventilation rate was not described in the ventilation rate equation (see electronic appendix), and this vapour pressure difference between greenhouse air and outdoor air was large at that time. To improve the model performance, the impact of the vapour pressure difference between greenhouse air and outdoor air on ventilation rate should be incorporated in the ventilation rate equation.

4.3. *A climate-controlled greenhouse in Texas, USA*

The model correctly predicted the temperature and the vapour pressure for both a winter and a summer period in Texas (Fig. 6). During the winter period, the temperature and vapour pressure were predicted in close agreement with the measurements, even when temperature and vapour differences between indoor air and outdoor air were large (Fig. 6a,c). During summer period, the temperature and vapour pressure were predicted in close agreement with the measurements (Fig. 6b,d). However, at some points in time small deviations between the measured and simulated greenhouse climate occurred. The daytime temperatures on DOY 160 and DOY 161 were underestimated at most by 3 °C.

Using the parameters of the stomatal resistance model of Stanghellini (1987), the simulated transpiration rate was

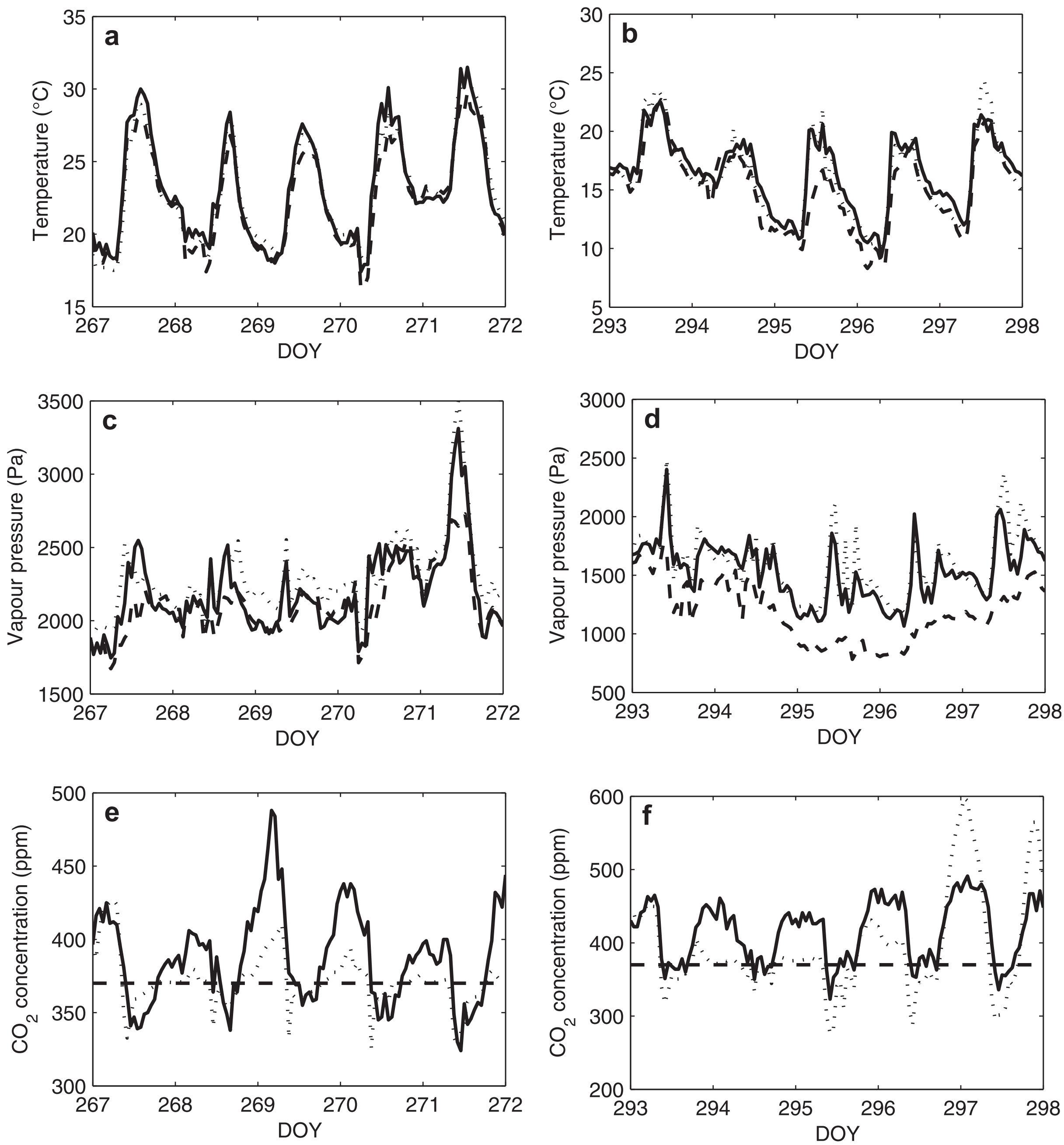

Fig. 4 – Temperature (a, b), vapour pressure(c, d) and the CO_2 concentration (e, f) of measured greenhouse air (solid line), simulated air (dotted line) and outdoor air (dashed line) for the hot period (DOY 267–272) and for the cold period (DOY 293–298) in Sicily.

underestimated with respect to the measured transpiration rate during daytime in the summer. Those parameters, however, were determined empirically for vapour pressure differences between leaf and air up to 0.9 kPa. The vapour pressure differences in Texas, however, could reach 4.0 kPa, a value where extrapolation of Stanghellini's (1987) function would have a considerable impact (see electronic appendix Eq. (49)). Therefore the parameter of the stomatal resistance model describing stomatal reaction to vapour pressure difference, i.e. c_{evap4}^{day} was reduced to 10% of its original value, which yielded better results for crop transpiration We did not investigate whether other models of stomatal conductance, such as Blonquist, Norman, and Bugbee (2009) would perform better.

4.4. *A pad and fan-cooled greenhouse in Arizona, USA*

The model correctly predicted the temperature and vapour pressure for a pad-cooled greenhouse in Arizona for various ventilation rates during the day in the summer period (Fig. 7). The model slightly underestimated the temperature and the vapour pressure of the greenhouse air (Fig. 7a) only for the lowest ventilation rate. This underestimation could have been

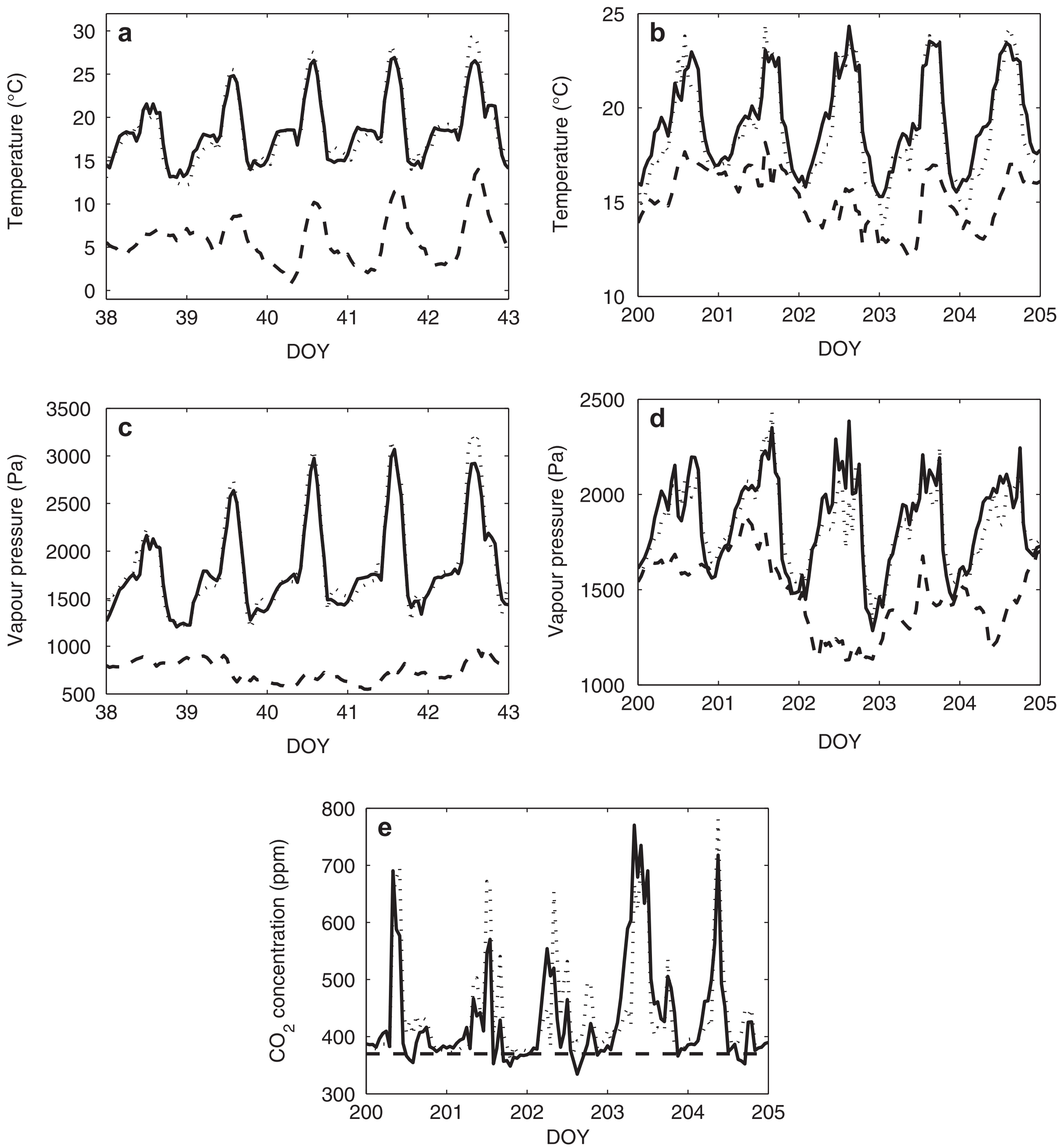

Fig. 5 – Temperature, vapour pressure and the CO_2 concentration of the measured greenhouse air (solid line), simulated air (dotted line) and outdoor air (dashed line) for the winter period (DOY 38–43) and for the summer period (DOY 200–205) in The Netherlands.

caused by assuming that the greenhouse was a perfectly stirred tank, which is not the case when a pad and fan system is used. Specifically, a pad and fan cooling system causes horizontal temperature and vapour pressure gradients (Sabeh, Giacomelli, & Kubota, 2006).

Furthermore, the underestimation of the vapour pressure at the lowest ventilation rate might have been caused by an underestimated transpiration rate. The transpiration rate was simulated using a constant boundary layer resistance, which was valid for naturally ventilated greenhouses with an indoor wind speed around 0.10 m s^{-1} (electronic appendix). By using this constant boundary layer resistance in a pad and fan-cooled greenhouse with a considerably higher indoor wind speed, the impact of higher wind speeds on boundary layer resistance was not taken into account, which would ultimately result in an underestimated transpiration rate. However, the underestimation of the transpiration rate negatively affected the simulated indoor climate only at the lowest ventilation rate (Fig. 7a). At higher ventilation rates, the impact of the pad and fan system on energy and vapour

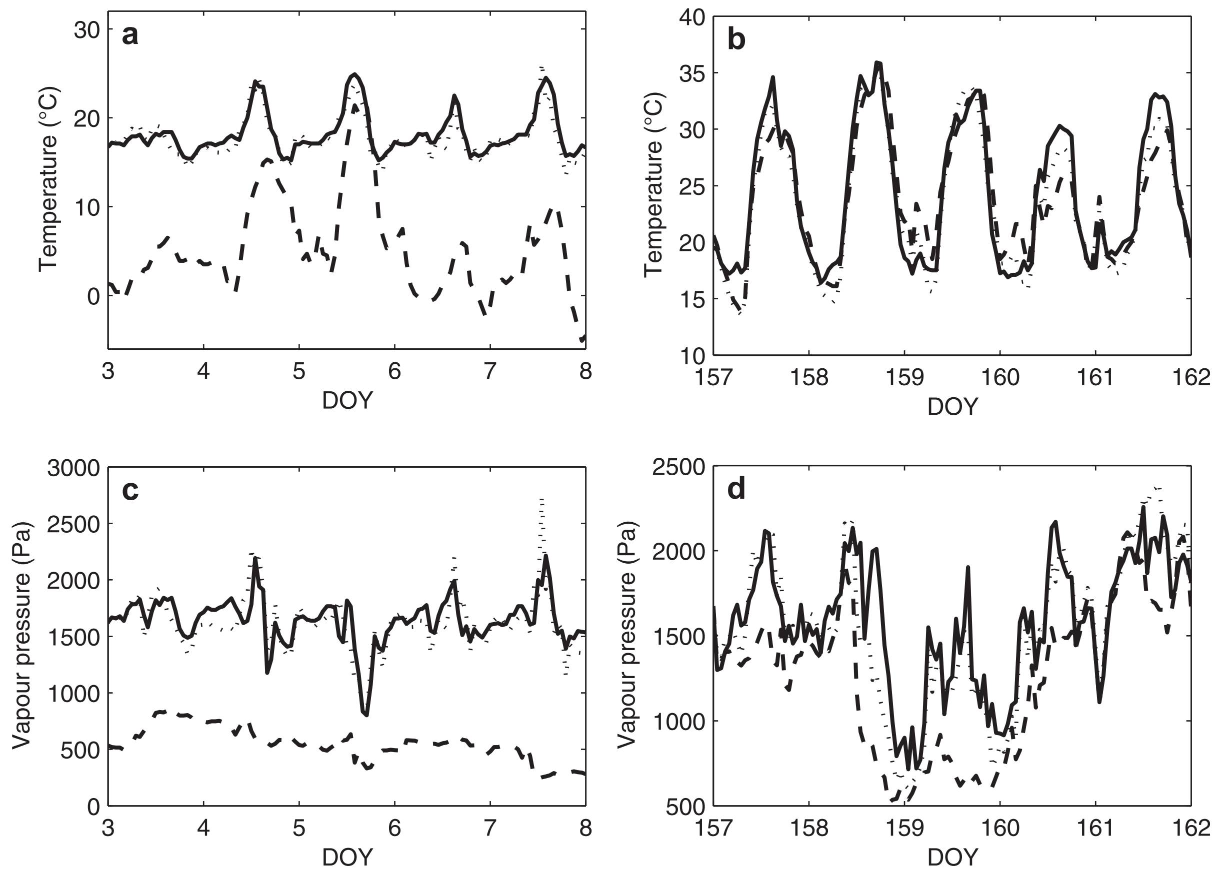

Fig. 6 – Temperature and the vapour pressure of measured greenhouse air (solid line), simulated air (dotted line) and outdoor air (dashed line) for the winter period (DOY 3–8) and for the summer period (DOY 157–162) in Texas, USA.

balance became dominant with respect to transpiration rate, which resulted in an accurate prediction of temperature and vapour pressure (Fig. 7b–d).

4.5. *Overall model performance*

The model performance in terms of RRMSE is shown in Table 3. In addition to the qualitative model evaluation, the more quantitative model performance evaluation, based on the RRMSE, clearly indicates the ability of the model to describe the greenhouse indoor climate for different designs, locations and outdoor climate conditions. In almost all cases, the RRMSE was well below the required threshold of 10%. Exceptions were the vapour pressure of the air in Texas during the winter and summer periods (10.0% and 12.8% respectively), in Arizona at the lowest ventilation rate (19.8%) and the CO_2 concentration in both Sicily in the autumn period (11.7%) and in The Netherlands in the winter period (12.3%).

For large differences between the indoor climate and the outdoor climate, which occurred during the winter in the Netherlands and in Texas, and during sunny summer days in Arizona, the model correctly predicted the indoor climate. This means that the physical properties and the design elements had properly been modelled.

The calculated errors could be decreased by reducing the measurement errors of the measurement boxes. These measurements contained errors due to measurement inaccuracy and because one measurement box was unable to represent the climate of the whole greenhouse section, as a greenhouse is not a perfectly stirred tank. Specifically, Bontsema, Gieling, Kornet, Swinkels, and Van Henten (2008) measured the relative errors of commercial measurement boxes for the air temperature, relative humidity and CO_2 concentration, which were 1.4%, 2.8% and 7.2% respectively. Although the measurement boxes were calibrated and placed at the centre of a greenhouse section, more accurate and randomly placed measurement boxes would reflect the overall indoor climate better. More accurately measuring indoor climate could in turn decrease the RRMSE.

Model performance was measured at a time interval of 1 h. This time interval was sufficiently small to describe the daily greenhouse climate fluctuations needed for greenhouse design optimisation. Therefore, the model accuracy for smaller time intervals was not analysed. However, the model performance will probably not decline significantly with smaller time intervals because the model is described using first order differential equations and solved with a solver with a variable time step.

5. Discussion

To design and optimise protected cultivation systems for the wide variety of climate conditions that can be expected

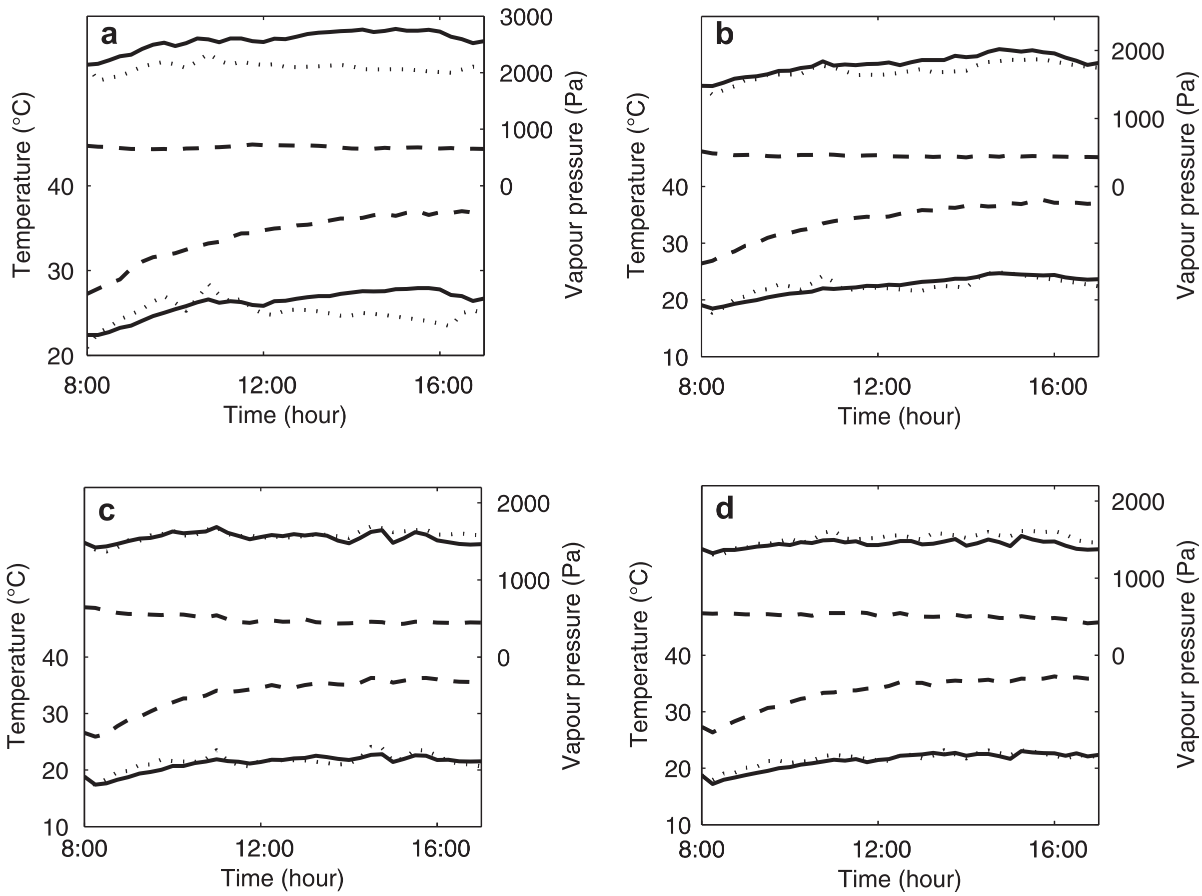

Fig. 7 – Temperature and the vapour pressure of the measured greenhouse air (solid line), simulated air (dotted line) and of outdoor air (dashed line) for data obtained with four ventilation rates through the pad: 0.016 m^3 m^{-2} s^{-1} (a), 0.034 m^3 m^{-2} s^{-1} (b), 0.047 m^3 m^{-2} s^{-1} (c) and 0.060 m^3 m^{-2} s^{-1} (d) in Arizona, USA.

around the world, it is essential to have a model that correctly predicts the indoor climate, not only as a function of a wide range of outdoor climate conditions, but also as a function of a wide range of construction elements and climate conditioning equipment.

Accordingly, the model developed here, fulfilling the requirement of using differentiable equations, was validated for a variety of greenhouse designs and outdoor climate conditions. Without calibration (except in one case), the model accurately described the greenhouse climate, both in terms of dynamic responses and absolute values. Quantitative evaluation of the model performance using an RRMSE criterion supported these findings. In more than 78% of the cases, comparison of simulations and measurements of the indoor climate yielded an RRMSE of less than 10%. This model performance, in terms of RRMSE, corresponds with values obtained by other climate modelling studies as reported by Baptista (2007). Given these results, the model is considered to be sufficiently accurate and generic to be used as a key component for developing a model-based greenhouse design method. In particular, our model includes relevant processes for greenhouse design, such as FIR radiation fluxes, CO_2 fluxes and a detailed transpiration module, that are not present in other models, such as the educational climate simulation model of Fitz-Rodríguez et al. (2010).

However, since our aim was to develop a design method that focussed on the optimisation of a set of design elements, model aspects that might be relevant may have been neglected or oversimplified. Therefore, whenever better or new modules are available, they can be easily incorporated into the design method. Some issues that might improve the generality of the model-based design method are discussed in more detail here. In particular, a module that describes the light transmission as function of season, latitude, orientation, shape, gutter and ridge height and type of cover material might enable the optimisation of the greenhouse height and the roof slope. Since radiation diffusing materials seem promising in areas with high solar radiation, differentiation between direct and diffuse radiation would allow diffuse properties of cover materials to be optimised also in relation to diffusion. Additionally, modules of other climate modification techniques such as co-generation of heat and electricity, artificial photosynthetic lighting, an active heat buffer, a heat pump and a solar heat collector might be incorporated.

To quantify the impact of uncertain model aspects on indoor climate prediction systematically, sensitivity analysis techniques can be used (Chalabi & Bailey, 1991; Nijskens, De Halleux, & Deltour, 1991). Although a sensitivity analysis was not performed in this paper, our results allow for some possible model improvements to be indicated. Firstly,

Table 3 – Relative root mean square error (RRMSE) values used to evaluate the ability of the model to describe the air temperature, the humidity and the CO_2 concentration in the four greenhouses located in Sicily, The Netherlands, and in Texas and Arizona in the USA. The crosses indicate that measurements of the associated variables were not available.

Location	DOY	Ventilation flux of the pad and fan cooling mechanism ($m^3\ m^{-2}\ s^{-1}$)	Relative root mean square error (RRMSE) (%)		
			T_{air}	VP_{air}	CO_{2air}
Sicily, Italy	267–272	–	3.5	7.0	7.1
Sicily, Italy	293–298	–	6.6	8.9	11.7
The Netherlands	38–43	–	6.2	6.4	x
The Netherlands	200–205	–	5.3	5.7	12.3
Texas, USA	3–8	–	6.0	10.0	x
Texas, USA	157–162	–	6.8	12.8	x
Arizona, USA	139	0.016	8.0	19.8	x
Arizona, USA	151	0.034	4.5	6.8	x
Arizona, USA	131	0.047	4.1	3.9	x
Arizona, USA	132	0.060	3.3	5.9	x

according to Campen and Bot (2003), the ventilation rate may depend strongly on wind direction, whereas the modelled ventilation rate was not, which could explain some of the deviations. The ventilation rate influences in turn the indoor temperature, vapour pressure and CO_2 concentration.

Although the sky temperature and the external soil temperature were not measured but estimated, the indoor temperature was accurately predicted by the model because all the associated RRMSE values were lower than 10%. Apparently, the small impact of these estimated values on temperature prediction was caused either by accurate calculations or by the negative feedback mechanisms implemented in the model, such as the canopy transpiration and the capacity of the soil to store heat. Nevertheless, the sky temperature and external soil temperature should be measured in future research to improve model performance. Additionally, pipe temperature was considered as a model input, whereas for greenhouse design optimisation the input must be energy and the pipe temperature must be a state variable as described in this study. Using the pipe temperature as a model input did not undermine our validation results because in the long term the heat input supplied to the heating pipes equals the heat output.

The vapour pressure of the air was predicted with reasonable accuracy; the associated RRMSE was higher than 10% for only three validation experiments. This attests to the ability of the model of Stanghellini (1987) to predict crop transpiration rate with fair accuracy under quite extreme climate conditions (VPD up to 2.0 kPa), as shown by Jolliet and Bailey (1992) and Prenger, Fynn, and Hansen (2002). In addition, the negative feedback between canopy transpiration and air vapour pressure ensures a reduced sensitivity of the vapour pressure to errors in the estimate of transpiration. Indeed, even for extreme climate conditions (temperature of 35 °C and VPD of 4.0 kPa), the air temperature was predicted with fair accuracy (RRMSE $<$ 10%). Nevertheless, the prediction of the transpiration rate could be improved further, by improving the empirical description of the stomatal resistance. In addition, making the boundary layer resistance wind speed dependent rather than constant might improve the simulation of the transpiration rate under higher wind speeds caused by e.g. pad and fan cooling.

The CO_2 concentration prediction was validated for only the two greenhouse designs for which the indoor data were available. The CO_2 concentration was predicted reasonably well for a greenhouse with and without CO_2 injection. The RRMSE of two out of three validation experiments was slightly higher than the requirement of 10%. CO_2 concentration prediction might be improved if the outdoor CO_2 concentration data were available. A secondary factor is the improvement of the prediction of the maintenance and photosynthesis fluxes.

Insight into these CO_2 fluxes would improve if greenhouse growers would measure the indoor and outdoor CO_2 concentration and the CO_2 supply. The lack of a strong negative feedback mechanism for the CO_2 concentration (Fig. 3) ensures that these sources of uncertainty might have a relatively large impact on the prediction of CO_2 concentration.

For greenhouse design purposes, deviations between simulated and measured CO_2 concentration at night are not important, because then the night time CO_2 concentration does not influence photosynthesis rate and crop yield. During day, these deviations do influence the photosynthesis rate, which in turn influence crop yield and the optimal greenhouse design problem. The impact of these deviations on optimal greenhouse design should be analysed with a sensitivity analysis of the optimal greenhouse design problem.

Regarding the design of the validation study, all the greenhouse functions were fulfilled by at least one design element (Table 1). Validation on function level was sufficient because it did not matter where a model flux came from, but it did matter how the model reacted to it. Consequently, the model was not validated for all the design elements shown in Fig. 2. It is, of course, advisable to validate the model aspects related to these design elements with data.

Differentiable switch functions were implemented instead of conditional "if/else" statements, due to the requirement that the model should consist of differentiable equations. Although the steep flanks of the switch function approached the conditional "if/else" statements, these functions might have an impact on model behaviour. Nevertheless, no discrepancies in model output between these approaches were shown, which support the feasibility of this approach.

6. Conclusion

A greenhouse climate model that describes the effect of outdoor climate and greenhouse design, including construction parameters and climate conditioning equipment on indoor greenhouse climate, was developed and validated. The aim is to use this model in a method to design greenhouses for the wide variety of climate conditions that can be expected around the world. To enable our findings to be implemented and reproduced, all model equations are presented in the paper and its electronic appendix.

For a broad range of greenhouse designs under varying climate conditions, the model predicted the greenhouse climate with reasonable accuracy. In our study, the greenhouse climate consisted of the temperature, vapour pressure and the CO_2 concentration. With the exception of one case, model parameters were not modified. In more than 78% of the cases, comparison of simulations and measurements of the indoor climate yielded an RRMSE of less than 10%. Additionally, the model fulfilled the requirements of containing the design elements that are sufficiently generic for a wide range of climate conditions and of being differentiable.

Given these results, the model is considered to be sufficiently accurate and sufficiently generic to be used for developing a model-based greenhouse design method. Therefore, the greenhouse climate model will be integrated into a model-based greenhouse design method, where it will be combined with a crop yield model and an economic model. An optimisation algorithm will then select the best design elements under the given climatic and economic conditions in order to maximize the profit of the grower.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biosystemseng.2011.06.001.

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