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Using Computational Fluid Dynamics to analyse the CO_2 transfers in naturally ventilated greenhouses

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bital CENTRO de INVESTIGACIÓN en BIOTECNOLOGÍA AGROALIMENTARIA

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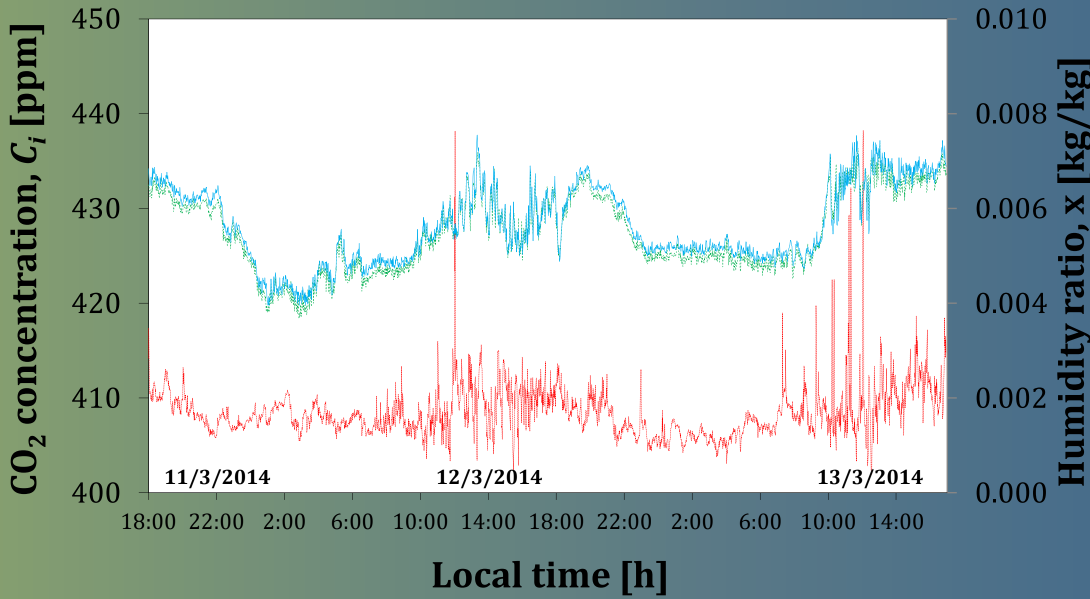
Introduction

Greenhouse microclimate is characterised by the four main factors that affect crop development: solar radiation, air temperature and humidity and CO_2 concentration.



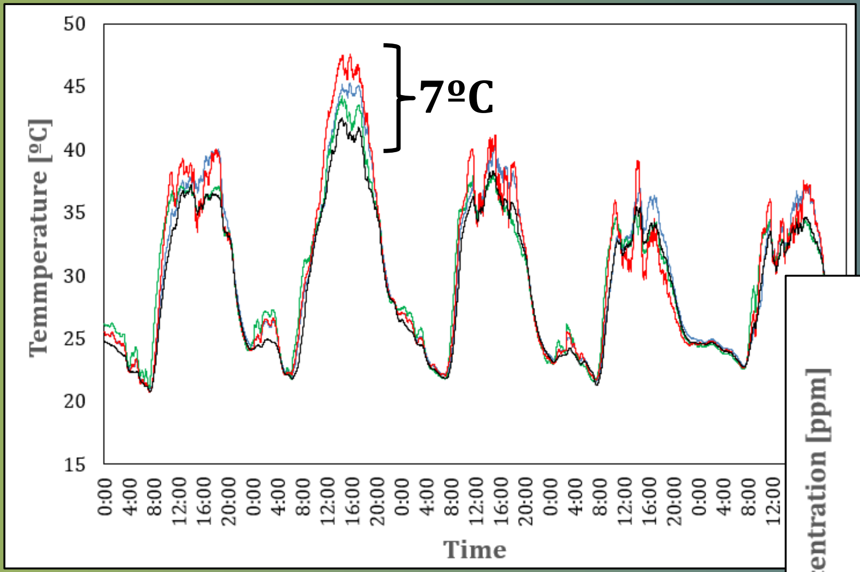
Classic climate models developed for control purposes, based in the energy and mass balances inside the greenhouse, suppose the homogeneity of these parameters.

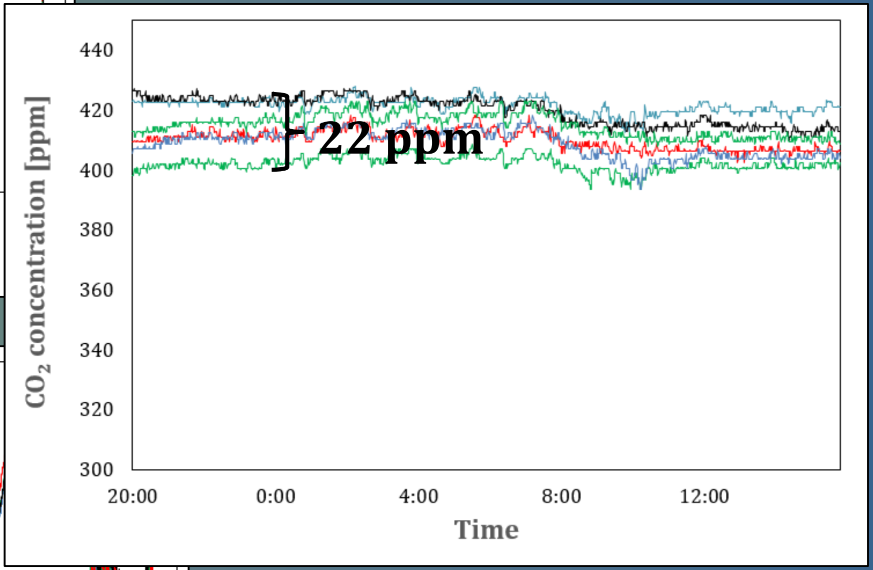
Introduction

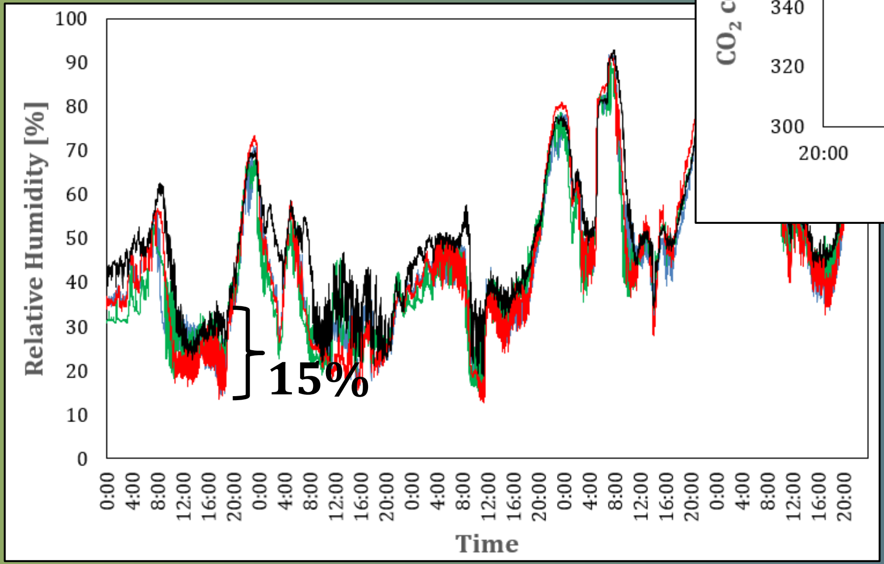
However, the great dimensions of modern commercial greenhouses generate differences in the values of these parameters that can affect the development of plants, resulting in differences of productivity, water consumption or heating requirements.

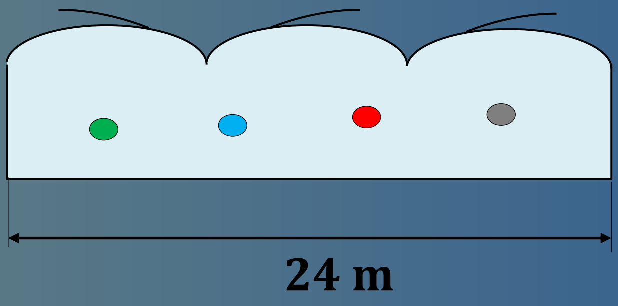
Introduction

Great differences were observed in values of this parameters inside greenhouses.









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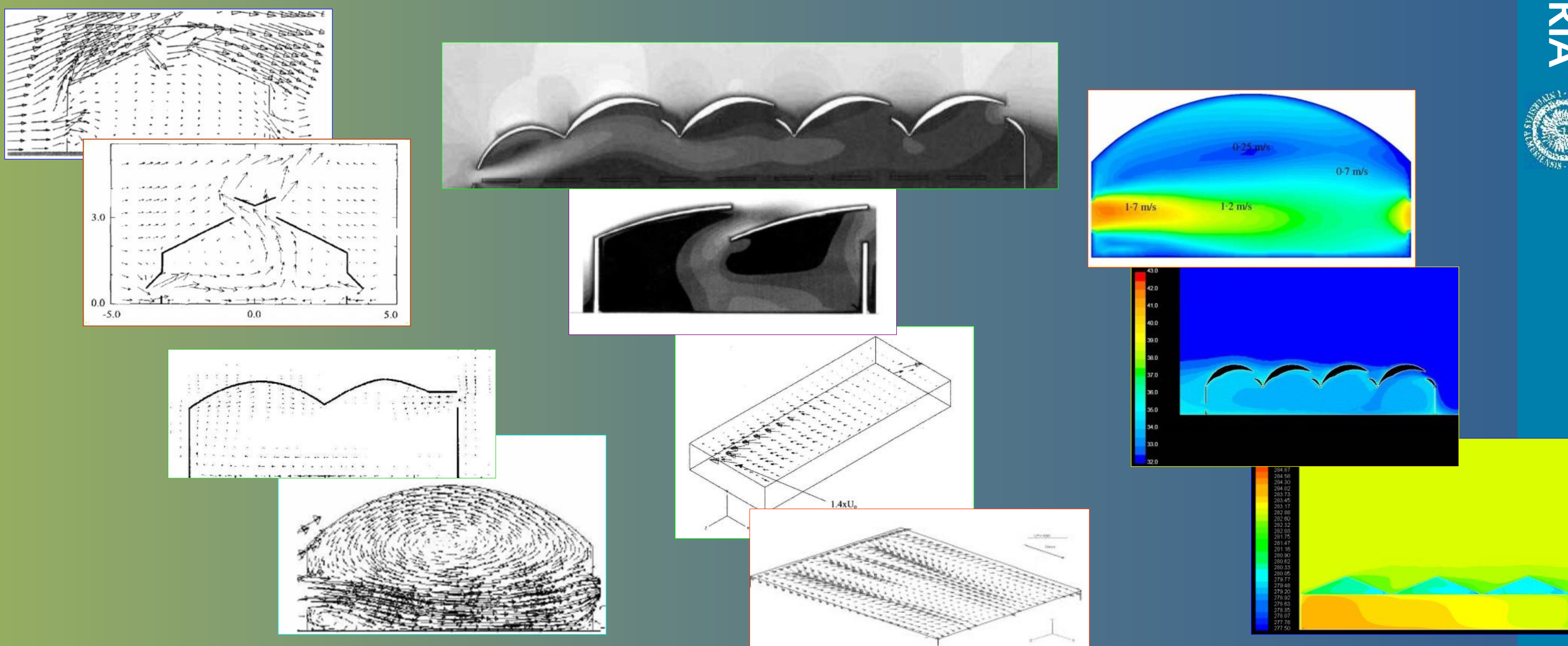
Introduction

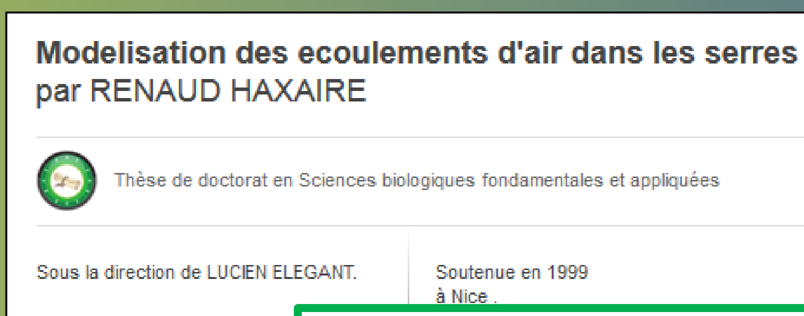
As consequence of the necessity of knowledge of the distribution of air temperature, humidity and CO_2, Computational Fluid Dynamic software began to be used at the end of the last century.



Introduction

The use of the CFD technique to simulate greenhouses microclimate requires the modelling of the effect of plants in the transport of energy, water vapour and CO_2.

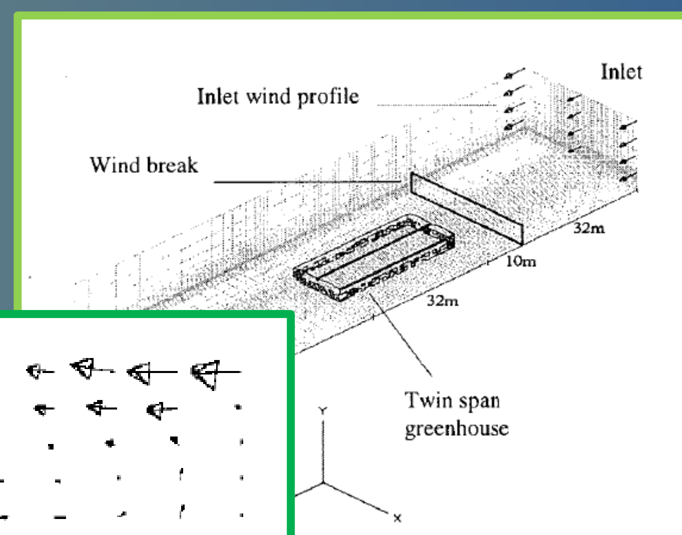
Haxaire (1999) included the effect of resistance of plants to the air movement using a drag coefficient C_d characterising a tomato crop.

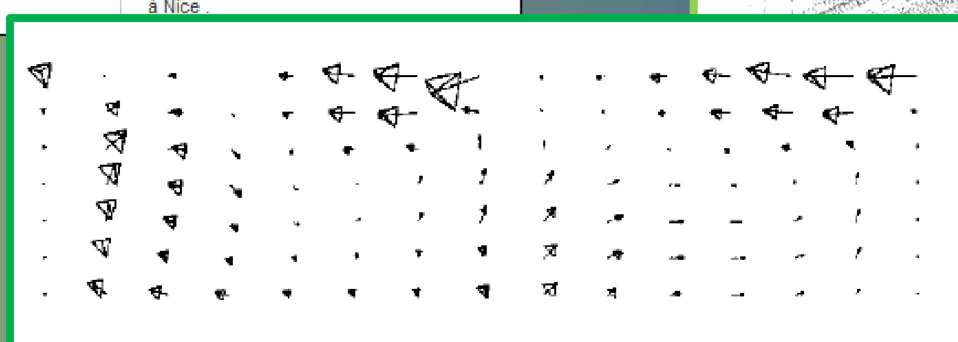

Modelisation des ecoulements d'air dans les serres
par RENAUD HAXAIRE

Thèse de doctorat en Sciences biologiques fondamentales et appliquées

Sous la direction de LUCIEN ELEGANT.

Soutenue en 1999
à Nice .





Introduction

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Boulard and Wang (2002) simulated crop transpiration inside a tunnel greenhouse customising the CFD program to include models of crop heat exchanges and global solar radiation.

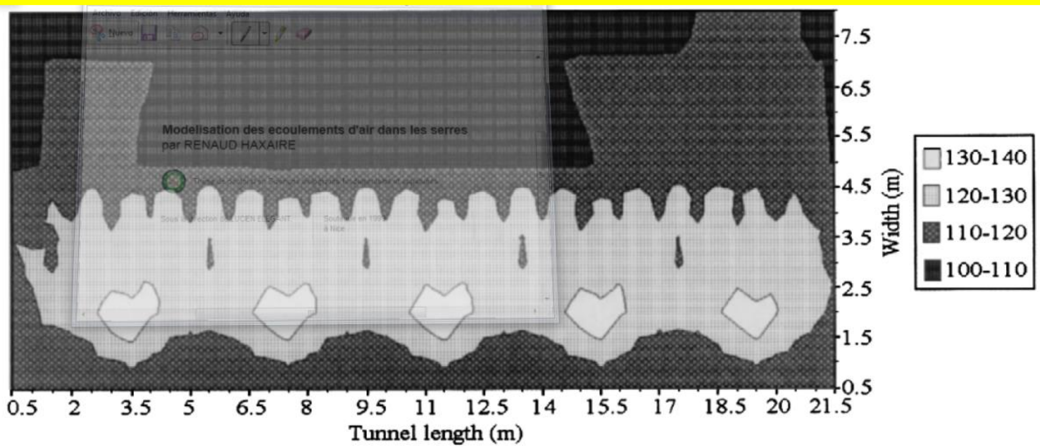

Fig. 7. Simulated average (on the diurnal period) solar radiation distribution in E–W oriented tunnel on 21 March under clear weather conditions. The outside average solar radiation was 196 W m^{-2}. The unit of solar radiation is in W m^{-2}.

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Computers and Electronics in Agriculture 34 (2002) 173–190
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Experimental and numerical studies on the heterogeneity of crop transpiration in a plastic tunnel

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Introduction

Fatnassi *et al*. (2002-2006) also incorporated the sensible and latent heat exchanges between plants and air inside greenhouse including in the CFD software programed user-defined functions (UDF).

Simulation of Air Flux and Temperature Patterns in a Large Scale Greenhouse Equipped with Insect Proof Nets

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Optimisation of Greenhouse Insect Screening with Computational Fluid Dynamics

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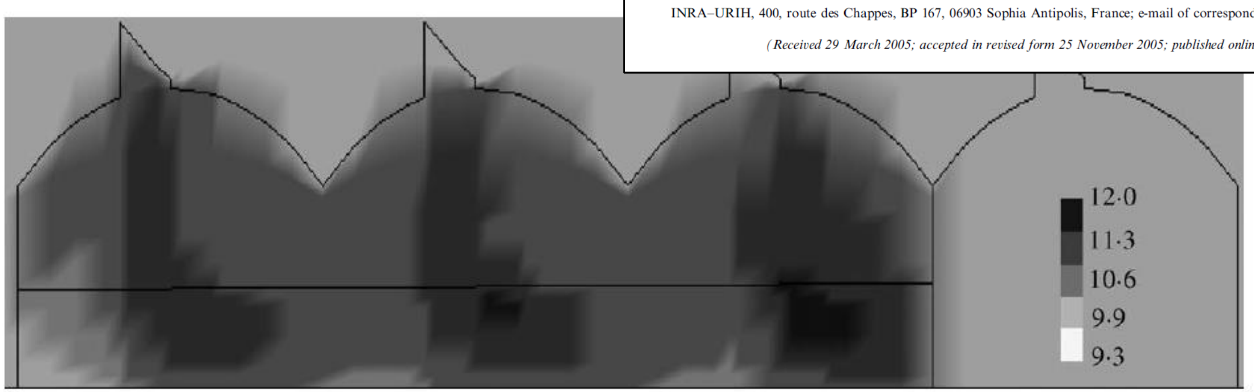

Fig. 13. Air humidity field in g kg^{-1} within the greenhouse for the configuration with open windward and side openings and with anti-Thrips nets on the vents (inside horizontal line refers to crop height)

Roy *et al*. (2014) also programed an UDF to include a photosynthesis model (Thornley, 1976) to compute the plants absorption of CO_2 inside a greenhouse with CO_2 supply.

Experimental and CFD Results on the CO_2 Distribution in a Semi Closed Greenhouse

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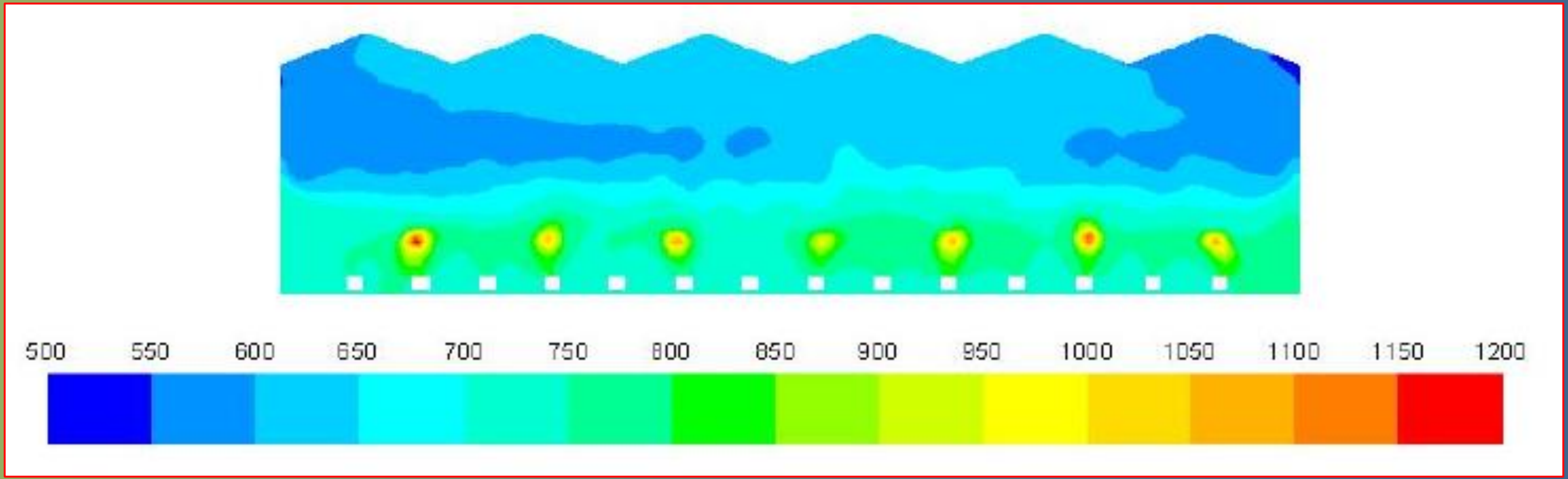
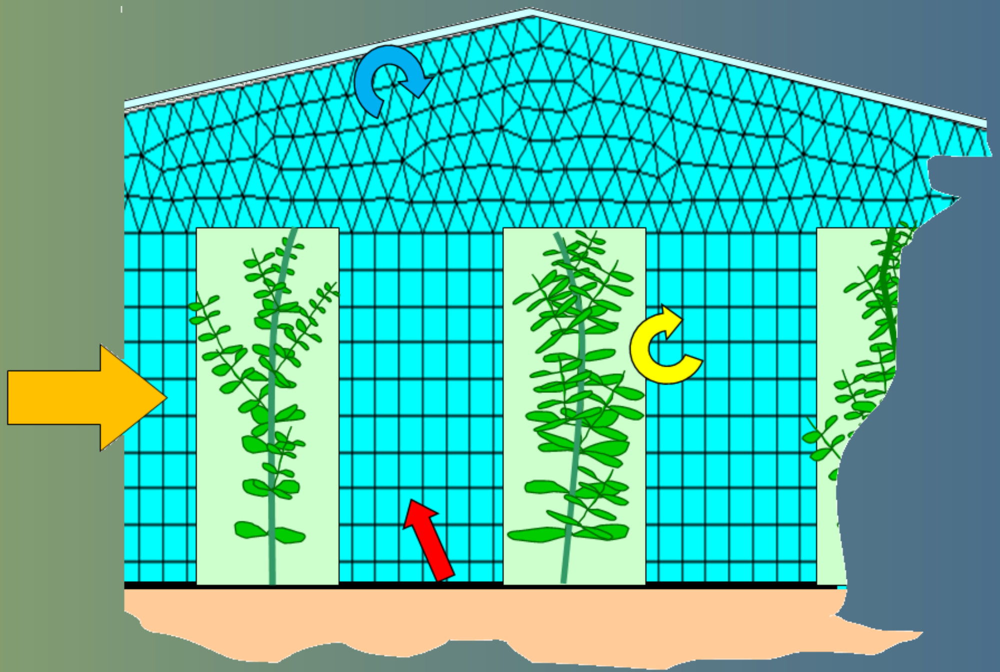


The dynamic evolution of greenhouse microclimate includes energy transfers (convection, conduction, radiation and heat storage) and mass transfers (air, water vapour and CO_2) between different elements composing a complex system: a fluid being a mixture of gases, greenhouse cover, insect-proof screens, soil and plants.



Objective

The objective of the present work was to develop and validate a bi-dimensional CFD model to simulate the plants photosynthesis inside a naturally ventilated *Almería*-type greenhouse.

To include photosynthesis in the numeric model a UDF was programed.

Materials and methods

Experimental setup

Experimental measurements were carried out in a five spans Almeria type greenhouse with a “*raspa y amagado*” structure (with pitched roof), the most widely used in the province of Almería.

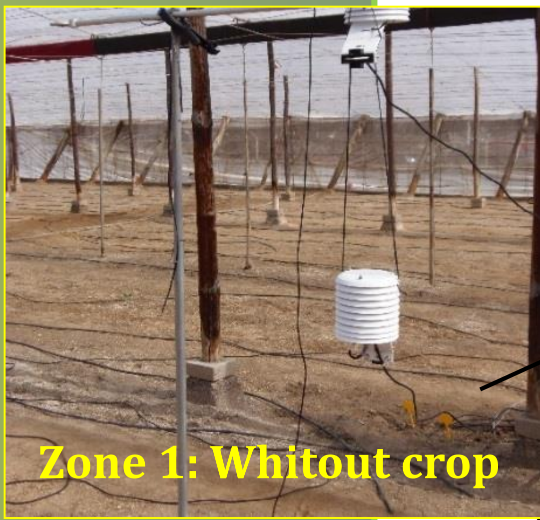
The experimental greenhouse (S_c=1850 m^2 & V_{inv}=4770 m^3) was located on the University of Almería's Campus (latitude: 36º 50', length: 2° 23', altitude: 2 m).

This greenhouse was equipped with two side openings and two roof openings perpendicular to the prevailing *Levante* winds from northeast.

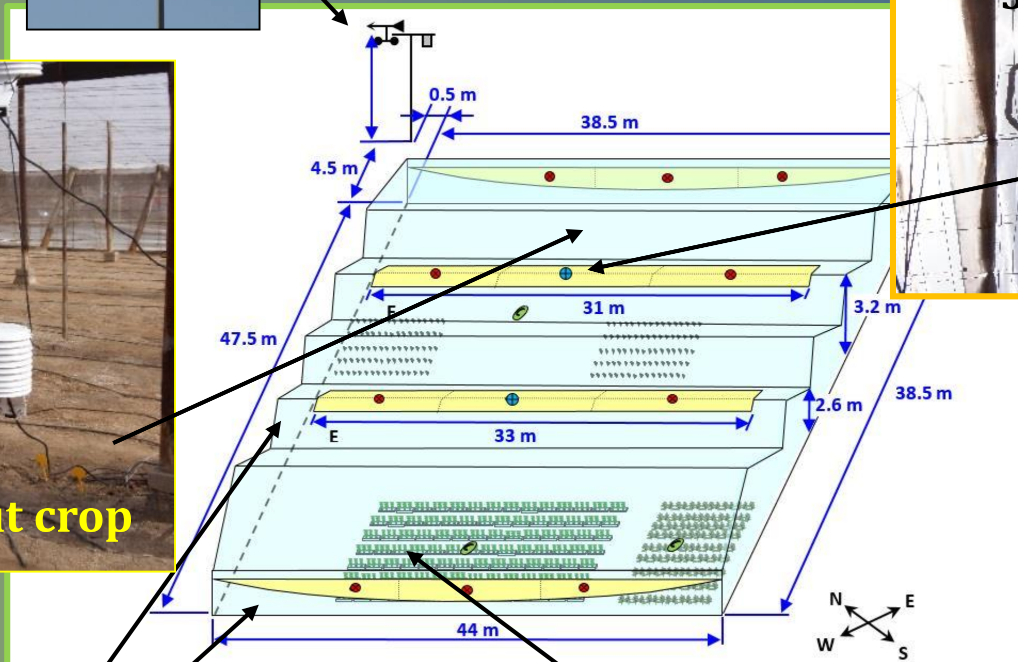
Side vents S_{VS}=56.8 m^2 (3%)

Roof vent openings S_{VR} =38.4 m^2 (2%)

Meteorological Station



Zone 1: Whitout crop



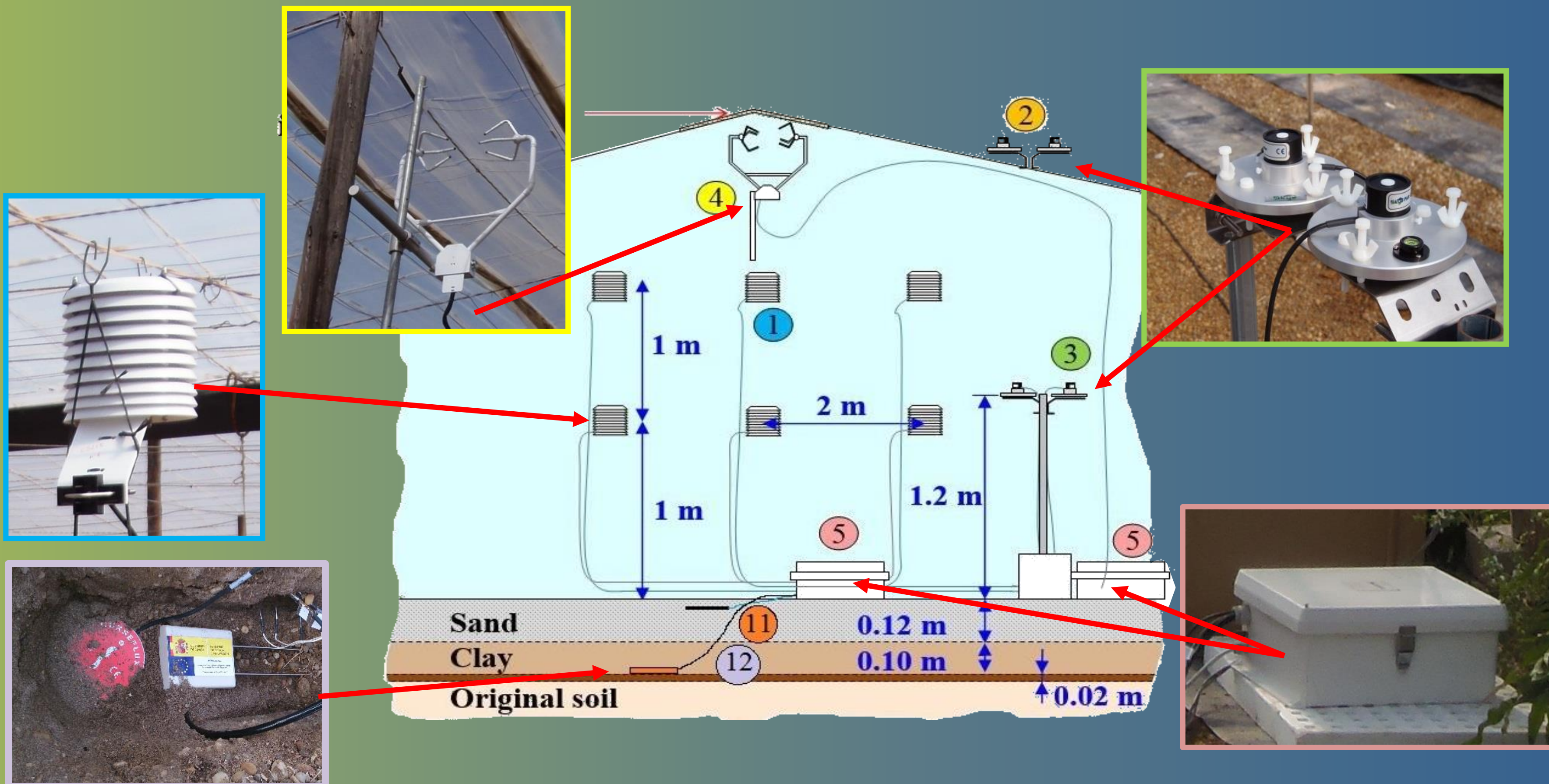
3D Anemometers

2D Anemometers

Zone 2: Tomato (soilless)

Inside air temperature T_i and absolute humidity x_i were measured at 6 locations below the two roof openings.

Sensors installed in zones 1 & 2



1 – psychrometric units inside radiation shield; 2 & 3 – pyranometers and quantum sensors; 4 – 3D sonic anemometer; 5 – dataloggers; 11 – thermistors; 12 – heat flux sensor.

Photosynthesis

The photosynthetic assimilation P_c and transpiration rates E_T of plants were measured with a portable sensor LCi Photosynthesis System.

The system also provides measures of PAR radiation and leaf temperature T_p (by energy balance).

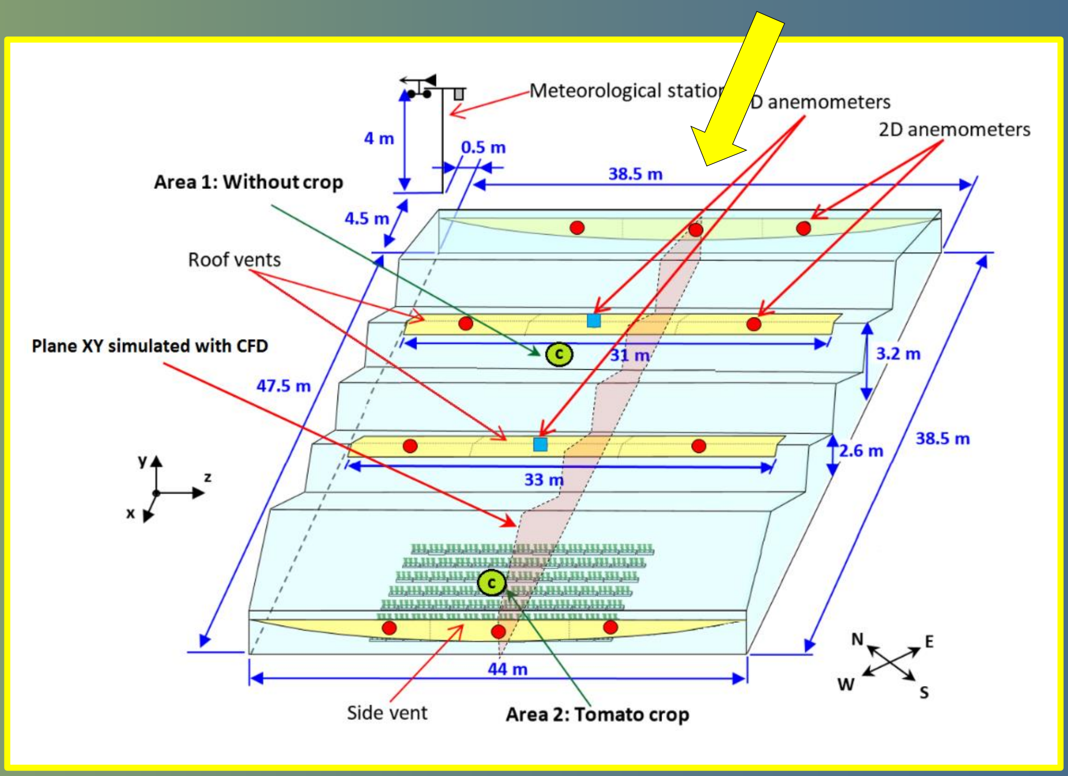
Sensors installed in the greenhouse

Validation of the CFD model

Parameter	*Sensor*	*Manufacturer*	*Range*	*Accuracy*
T_i – Inside air temperature	12 × CS215	Campbell Scientific Spain S.L., Barcelona, Spain	5 °C -40 °C	±0.4 °C
x_i – Inside absolute humidity			10-90%	±2%
R_{si} – Inside solar radiation	SP1110 pyranometer		350-1100 nm	±5%
R_{so} – Outside solar radiation				
Rn – Net radiation	NR-Lite	Kipp & Zonen B.V., Delft, Netherlands	±1000 W m^{-2}	±5%
T_{s0} – Soil temperature at 0.01 m and 0.1 m	Betatherm 100K6A thermistor	Measurement Specialties, Inc., Galway, Ireland	−5 °C-95 °C	±0.49 °C
$T_{s0.2}$ – Soil temperature at 0.2 m	TCAV thermocouple	Campbell Scientific Spain S.L.	−40 °C-375 °C	±1.5 °C
T_c – Cover temperature	OMEGA® OS540	Omega Engineering Inc., Stanford, USA	−20 °C-420 °C	±2%
Q_S – Soil heat flux at 0.2 m depth	HFP01	Hukseflux Thermal Sensors B.V., Delft, The Netherlands	±2000 W m^{-2}	−15 +5%
v_v – Air velocities in the openings	6 × Windsonic 2D	Gill Instrument LTD, Lymington, Hampshire, UK	0-60 m s^{-1}	±2% & ±3°
	2 × CSAT3 3D	Campbell Scientific Spain S.L.	0-30 m s^{-1}	±0.04 m s^{-1}
			−30 °C-50°C	±0.026 °C
P_L – Net photosynthesis	LCi-SD sensor	ADC Bio Scientific Ltd., Hoddsdon, UK	0-75 mbar (H_2O)	±2%
C_i – Inside CO_2 concentration			0-2000 ppm	
T_p – Leaf temperature	Betatherm 100K6A thermistor	Measurement Specialties, Inc., Galway, Ireland	−5 °C-95 °C	±0.49 °C
C_e – Ouside CO_2 concentration	TESTO® 445	Testo S.A., Cabrils, Spain	0-10000 ppm	± 50 ppm
u_o – Outside wind speed	Cup anemometer	Davis Instrument Corp., Hayward, USA	0-78 m s^{-1}	±5%
ϴ – Outside wind speed	Vane		0-360°	±7°
T_e – Outside air temperature	HOBO® Pro RH-Temp H08-032-08	Onset Computer Corp., Pocasset, USA	−20 °C-70 °C	±0.3 °C
x_e – Outside absolute humidity			0-100%	±3%

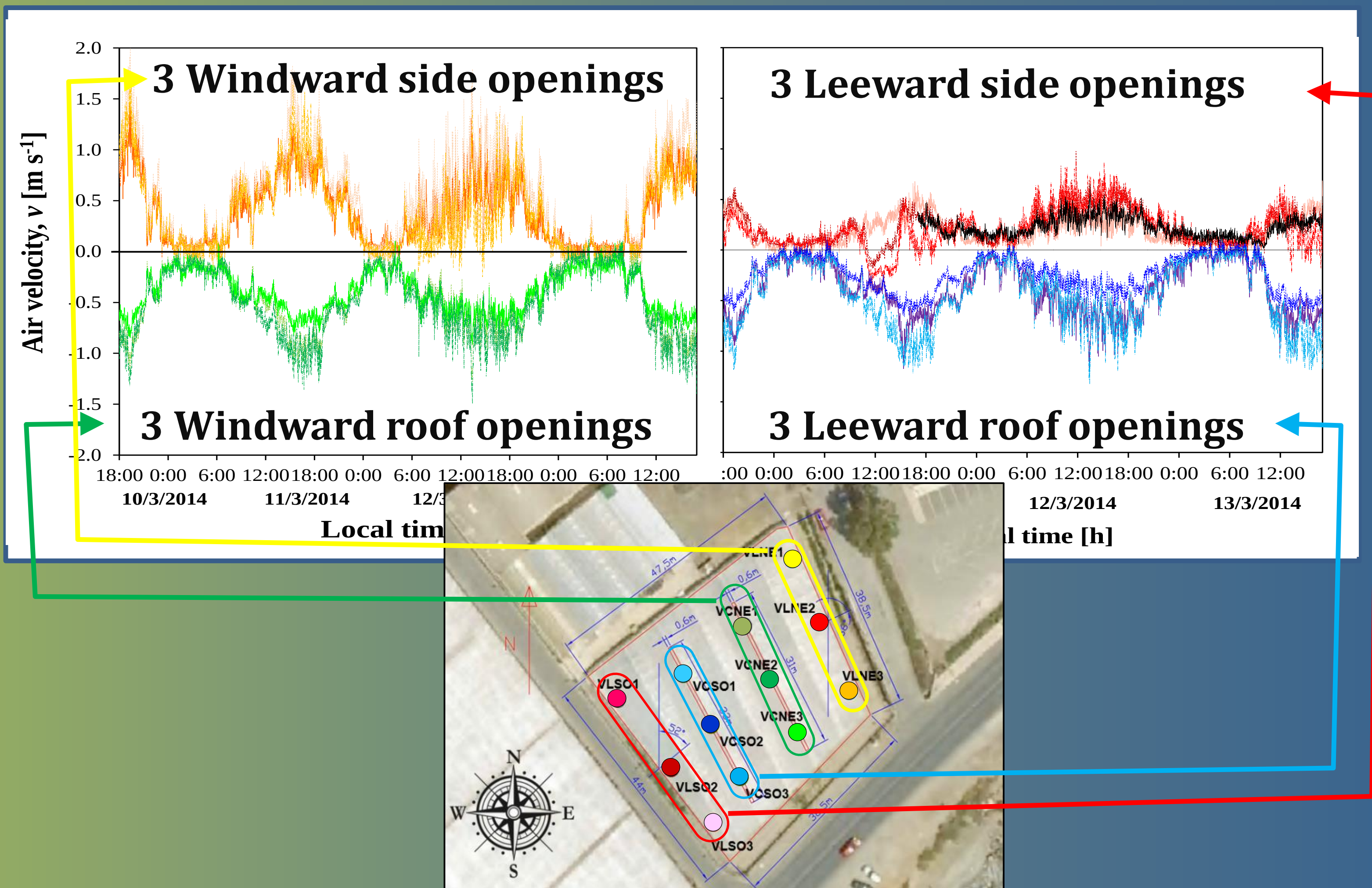
Numerical model

The greenhouse ridge was orientated northwest–southeast, practically perpendicular to the northeast *Levante* wind, and the structure had a sufficiently symmetrical shape to be simulated in two dimensions.



Numerical model

Air velocities measured by the three anemometers of each openings were very similar showing the symmetric airflow.



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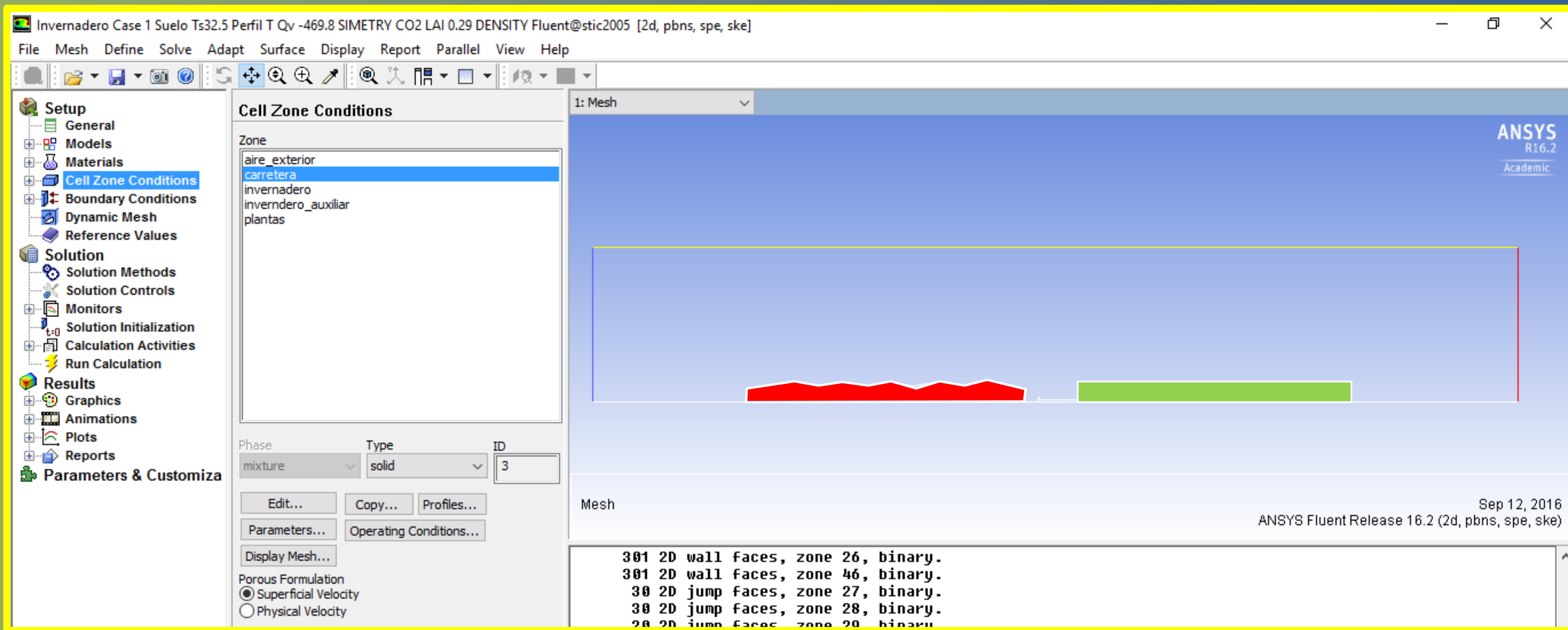
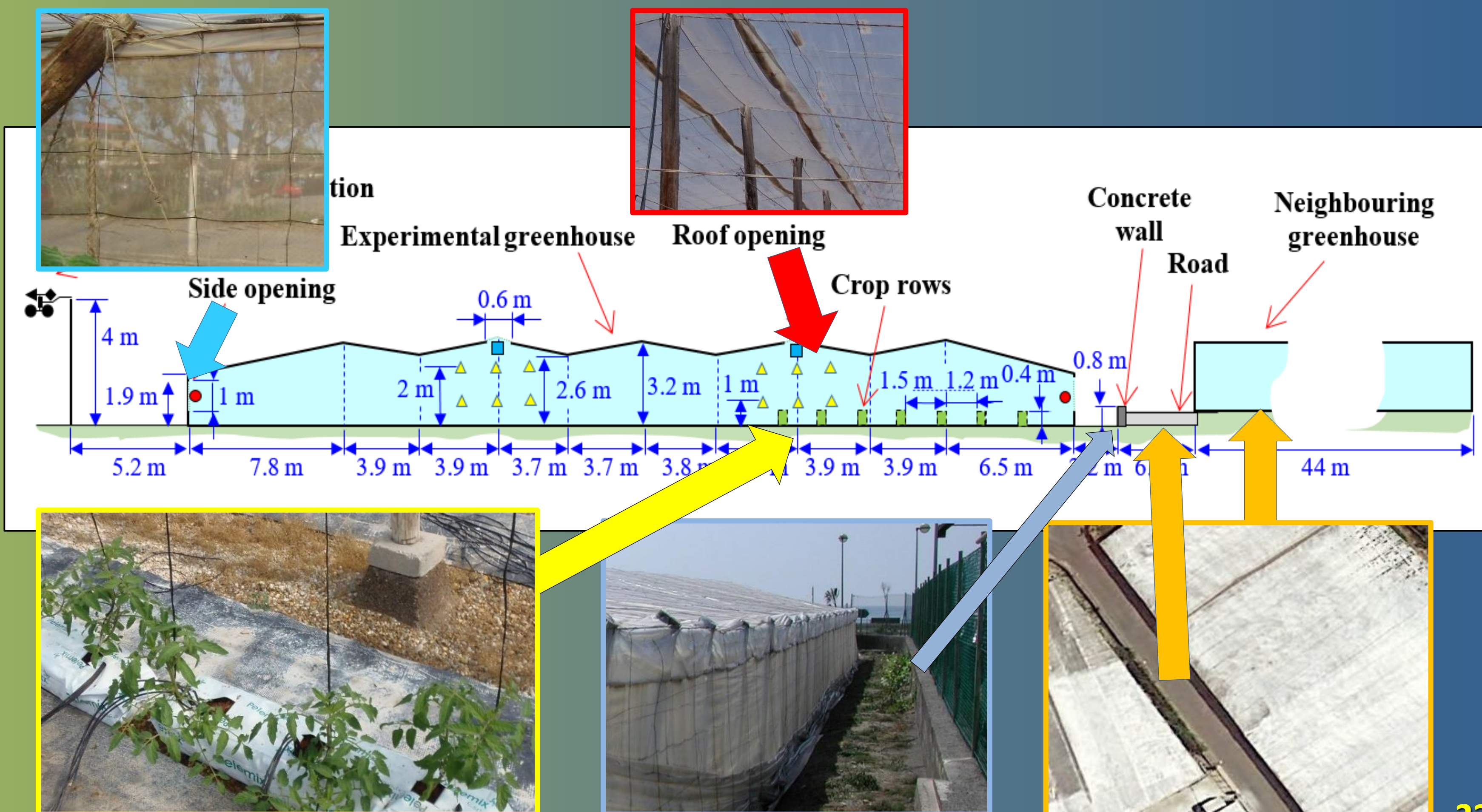
Numerical model

Airflow, temperature, humidity and CO_2 distributions were simulated inside the Almería greenhouse with the CFD commercial package ANSYS Fluent® v16.2.



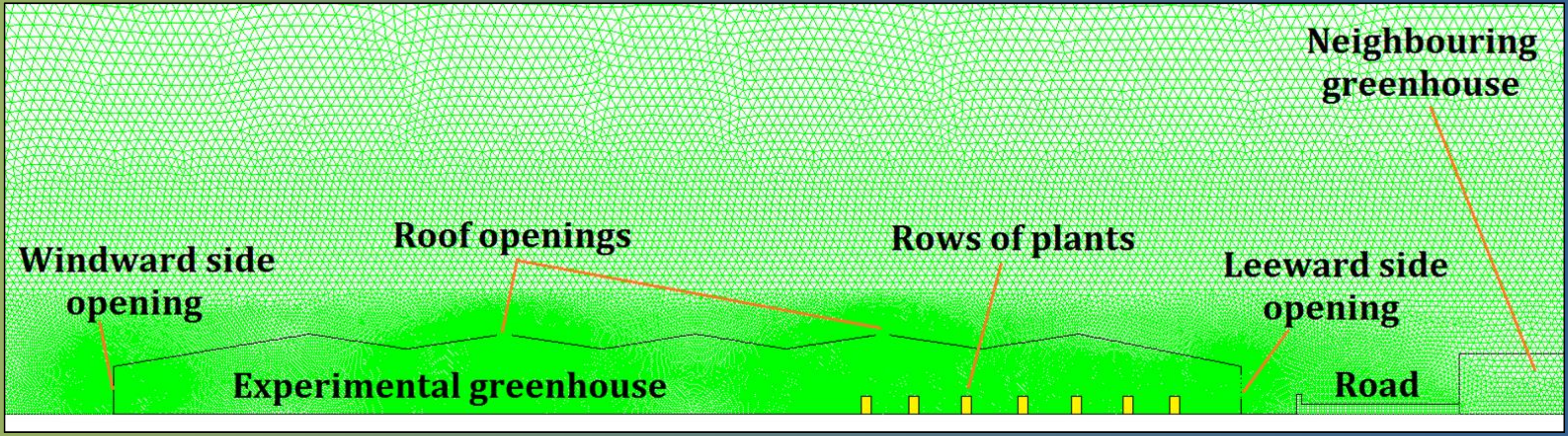
Numerical model

The model included the experimental greenhouse and a neighbouring greenhouse in a domain of 160 × 25 m.



Numerical model

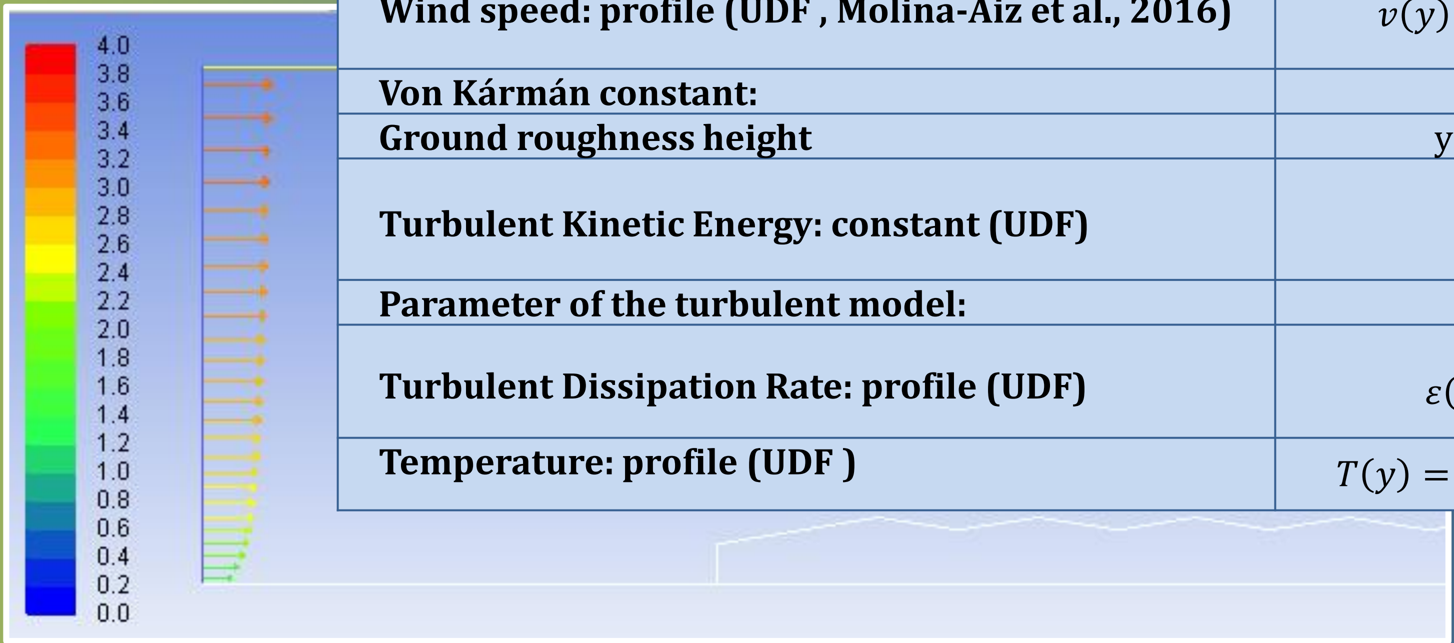
In the zone of the vent openings and around the crop, where the airflow description was more important, a higher grid density was used .



Parameters	
Domain size	160 m × 25 m
Element type	triangular & rectangular
Minimum elements size in the domain	0.005 m
Maximum elements size in the domain	0.5 m
Minimum orthogonal quality	0.45
Maximum orthogonal skew	0.37
Maximum aspect ratio	5.31
Cells number	156 693

Numerical model

In the windward limit of the domain a velocity inlet boundary condition was used programing an UDF to include velocity, turbulent dissipation rate and temperature profiles.



Boundary	Condition
Windward boundary:	Velocity inlet
Wind speed: profile (UDF , Molina-Aiz et al., 2016)	$v(y) = \frac{v^*}{K_{VC}} ln\left(\frac{y+y_0}{y_0}\right)$
Von Kármán constant:	K_{VC}=0.42
Ground roughness height	y_0=0.015 (m)
Turbulent Kinetic Energy: constant (UDF)	$\kappa = \frac{v^{*2}}{\sqrt{C_\mu}}$
Parameter of the turbulent model:	C_μ=0.09
Turbulent Dissipation Rate: profile (UDF)	$\varepsilon(y) = \frac{v^{*3}}{K(y+y_0)}$
Temperature: profile (UDF)	$T(y) = T_0 - \frac{T^*}{K_{VC}} ln\left(\frac{y+y_0}{y_0}\right)$

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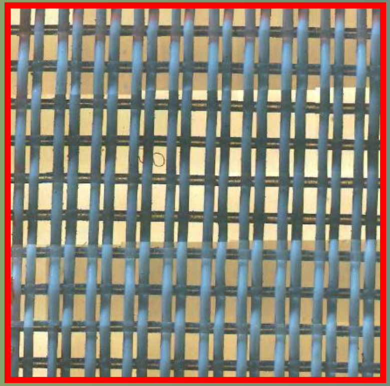
Insect-proof screens

The insect-proof screens were modelled with the Dupuit-Forchheimer equation, throughout the porous jump model of the CFD software:

$$\frac{\partial P}{\partial x} = -\left\{\frac{\mu}{\alpha}u_x + C_2\frac{1}{2}\rho|u_x|u_x\right\}$$

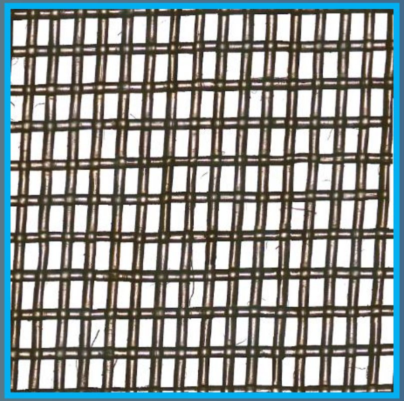
Roof vent openings



10×20 thread cm$^{-2$}

porosity $\varphi = 0.34$

Side openings



10×16 thread cm^{-2}

porosity $\varphi = 0.39$

Materials and methods

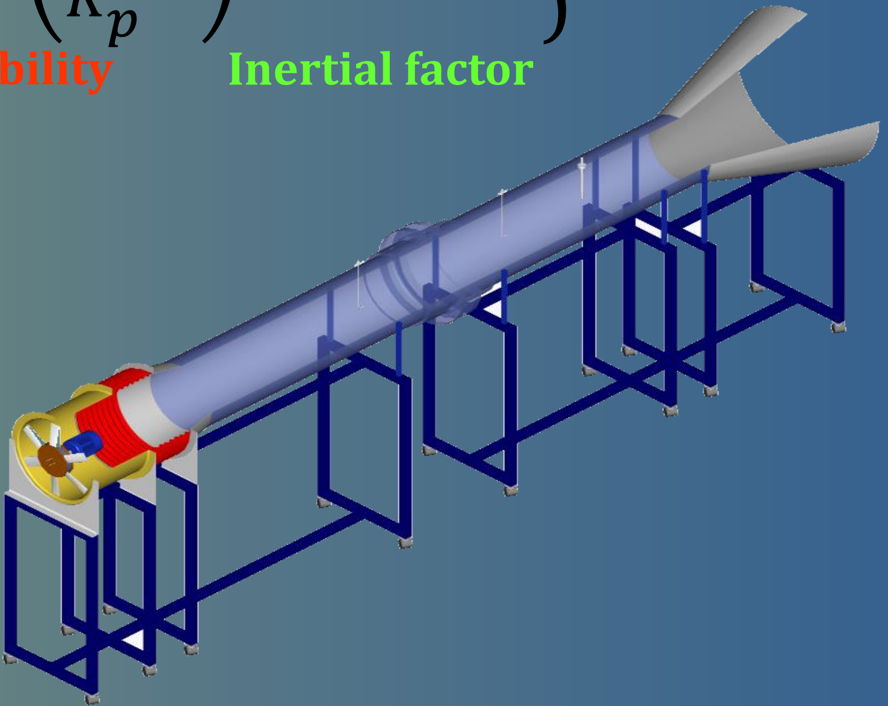
Insect-proof screens

Permeability K_p and the inertial factor Y were obtained from measurements in a wind tunnel (Molina-Aiz et al., 2009).

$$\frac{\partial P}{\partial x} = -\left\{\frac{\mu}{K_p} u_x + \left(\frac{Y}{K_p^{1/2}}\right) \rho |u_x| u_x \right\}$$

Permeability

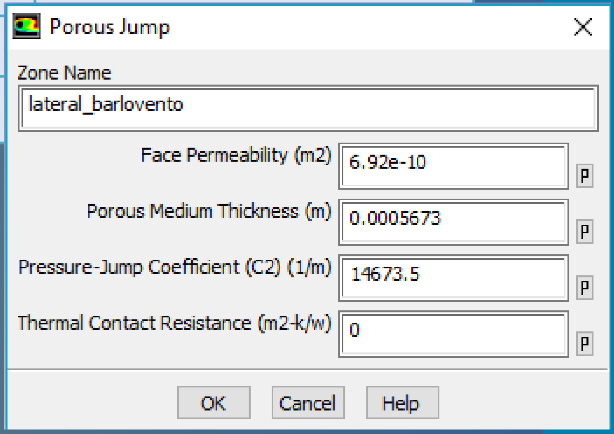
Inertial factor



Materials and methods

Insect-proof screens

Greenhouse openings	Side	Roof
	Measured values	
Porosity, φ_{is}	0.394	0.341
Thread density, ρ_{is} (threads cm^{-2})	10.2×16.3	9.9×19.8
Porous size (length × height), $L_{is} \times H_{is}$ (µm)	337.2 × 694.1	233.0 × 741.3
Thread diameter, D_{is} (µm)	278.2	271.9
Permeability, K_p (m^2)	6.92×10^{-10}	2.60×10^{-9}
Inertial factor, Y	0.193	0.254
	Values in the CFD porous jump model	
Thickness, e_{is} (m)	567.3×10^{-6}	371.3×10^{-6}
Face permeability: $\alpha = K_p$ (m^2)	6.92×10^{-10}	
Pressure-Jump coefficient : $C_2 = 2Y/K_p^{1/2}$ (m^{-1})	14673.5	



Modelling of the canopy

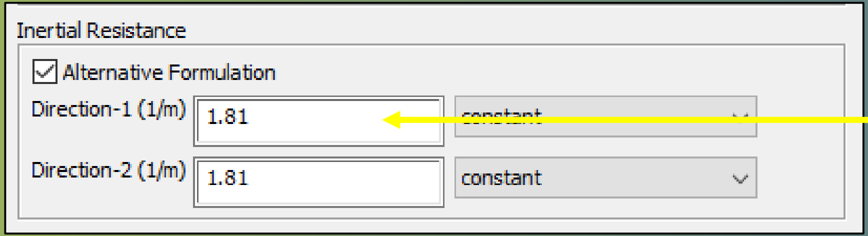
The effect of aerodynamic resistance produced by the airflow through the crop canopy was modelled as a porous media (Wilson and Shaw, 1977):

$$\frac{\partial P}{\partial x} = -C_d L_{ADr} \rho u_x^2$$

$\boldsymbol{C_d}$ canopy drag coefficient
$\boldsymbol{L_{ADr}}$ crop leaf area density ($m^2 \cdot m^{-3}$)
$\boldsymbol{v_x}$ air velocity ($m^2 \cdot s^{-1}$)

Modelling of the canopy

Measured values	
Plant leaf area, a_p (m^2)	0.2175
Distance between plant in the row, d_R (m)	0.5
Height of plants, h_p (m)	0.4
Gap between the rows, g_R (m)	1.2
Width of row, w_R (m)	0.3
Number of row, n_R	7
Leaf area index, L_{AI} ($m^2{}_{leaf}\, m^{-2}{}_{ground}$)	0.29
Leaf area density, L_{AD} ($m^2{}_{leaf}\, m^{-3}$)	0.72
Tomato drag coefficient, C_d	0.25
Values included in the CFD model	
Leaf area index inside the row, L_{AIr} ($m^2\, m^{-2}{}_{row}$)	1.45
Leaf area density inside the row, L_{ADr} ($m^2\, m^{-3}{}_{row}$)	3.63
Viscous resistance: C_1 (m^{-2})	0
Inertial resistance: C_2=2C_D L_{ADr} (m^{-1})	1.81



Numerical model

Ground surface and the plastic cover of the greenhouse were modelled as wall boundary conditions using values of measured temperatures.

Parameter	Symbol	Units	Day 1	Day 2
Outside temperature at 4 m height	T_o	(ºC) [(K)]	17.5 [290.7]	18.3 [291.5]
Outside wind speed at 4 m	v_R	$(m\ s^{-1})$	2.57	5.98
Outside H_2O mass fraction	x_o	$(kg\ kg^{-1})$	0.0065	0.0048
Outside CO_2 mole fraction	C_o	$(mol\ mol^{-1})$	0.000398	0.000409
Outside solar radiation	R_{So}	$(W\ m^{-2})$	763	825
Inside solar radiation	R_{Si}	$(W\ m^{-2})$	556	632
PAR measured at the leaves	Q_{PARL}	$(\mu mol\ m^{-2}\ s^{-1})$	790	837
Solar radiation absorbed by the crop	Q_{abC}	$(W\ m^{-2}{}_{leaf})$	132.7	140.7
Greenhouse cover temperature	T_c	(ºC) [(K)]	21.7 [294.9]	21.1 [294.3]
Soil temperature in the area without crop	T_{s-wc}	(ºC) [(K)]	32.5 [305.7]	27.9 [301.1]
Soil temperature in the area with crop	T_{s-c}	(ºC) [(K)]	30.1 [303.3]	26.6 [299.8]
Outside soil surface temperature	T_{so}	(ºC) [(K)]	25.1 [298.3]	23.8 [297.0]
Transpiration measured with LCi sensor	E_L	$(mol\ m^{-2}{}_{leaf}\ s^{-1})$	4.71×10^{-3}	3.88×10^{-3}
Transpiration source of H_2O in the model	S_{H2O}	$(kg\ m^{-3}\ s^{-1})$	3.08×10^{-4}	2.54×10^{-4}
Leaf temperature measured with the sensor	T_L	(ºC)	35.8	31.5
Sensible heat flux	S_h	$(W\ m^{-3})$	–469.8	–275.6

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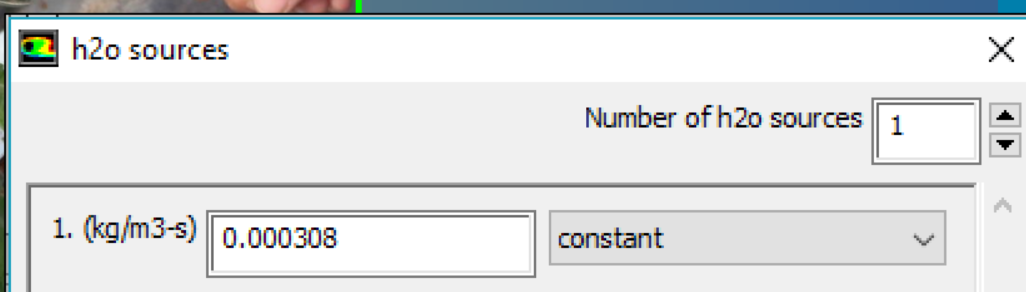
Numerical model

Crop transpiration E_L was modelled as a constant source of water vapour S_{H2O} equal to the values measured experimentally with the LCi sensor in the leaves of tomato plants.

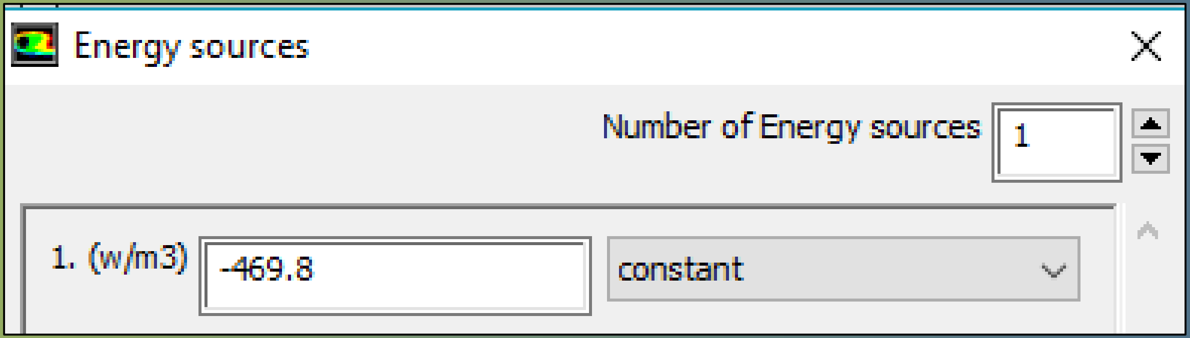


Numerical model

The sensible heat exchange was simulated as a constant volumetric heat source, computed as the difference between the radiation absorbed by the crop measured with the LCi sensor Q_{abC} and the latent heat removed by transpiration (Monteith and Unsworth 2013):

$$S_h = (Q_{abC} - E_L \lambda_{vm})\, L_{ADr} \text{ (W m}^{-3}\text{)}$$

E_L (mol_{H2O} m^{-2}_{leaf} s^{-1}) measured crop transpiration.
L_{ADr} (m^2_{leaf} m^{-3}_{row}) leaf area density in the plants rows.
λ_{vm} (J mol^{-1}) molar latent heat of vaporization of water.



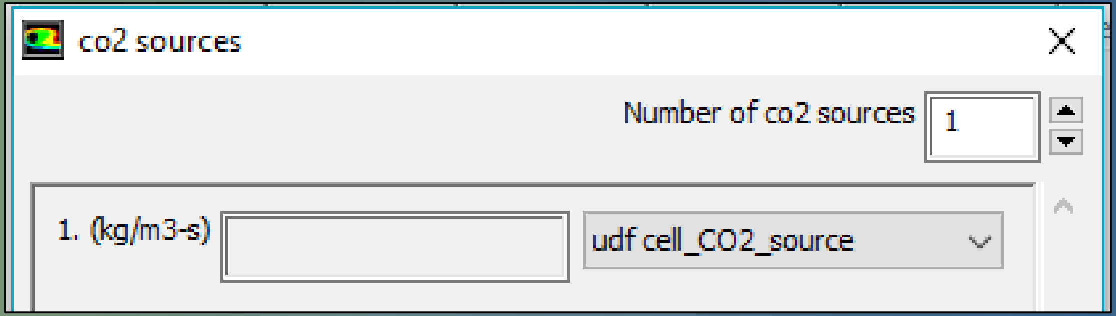
Numerical model

The ANSYS Fluent® solver computes the mass fractions of carbon dioxide in the air Y_{CO2} at each cell of the model domain solving the convection-diffusion equation for the CO_2 (ANSYS 2013):

$$\frac{\partial}{\partial t}(\rho Y_{CO2}) + \nabla \cdot (\rho \vec{v} Y_{CO2}) = -\nabla \cdot \vec{J}_{CO2} + S_{CO2}$$

Canopy photosynthesis rate P_{cg} was calculated in the UDF using the photosynthesis model of Acock (Acock et al., 1976) modified by Nederhoff and Vegter (1994b):

$$S_{CO2} = -P_{cCFD} = \frac{L_{ADr}}{L_{AI} 1000 \left[{}^{g}/_{kg}\right] 3600 \left[{}^{s}/_{h}\right]} \left(R' - P_{cg}\right) \left(\mathrm{kg}\ s^{-1} m^{-3}{}_{row}\right)$$



Numerical model

Canopy photosynthesis rate was calculated in the UDF using the photosynthesis model of Acock (Acock et al. 1971 & 1976) modified by Nederhoff and Vegter (1994b):

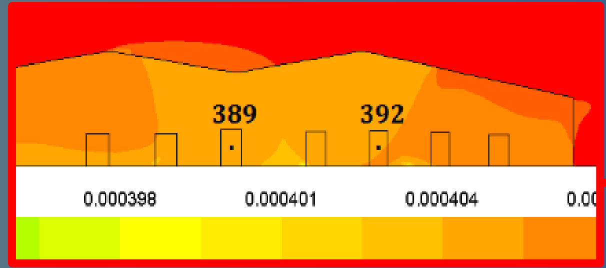
$$P_{cg} = \frac{\alpha_c J_0 \tau_c C' 3600 [s/h]}{\alpha_c J_0 + \tau_c C'} \ (\mathrm{g\ CO_2\ h^{-1}\ m^{-2}}_{\text{ground area}})$$

The light use efficiency of the plant canopy and the conductance of CO_2 were (Nederhoff and Vegter 1994b):

$$\alpha_c = \alpha_L \frac{1-\exp(-KL_{AI})}{1-m} \ (\mathrm{g\ CO_2\ J^{-1}})$$

$$\tau_c = \frac{a_A}{b_A K} ln\left(\frac{b_A S_0 K + (1-m)}{b_A S_0 K exp(-KL_{AI}) + (1-m)}\right) \ (\mathrm{m\ s^{-1}})$$

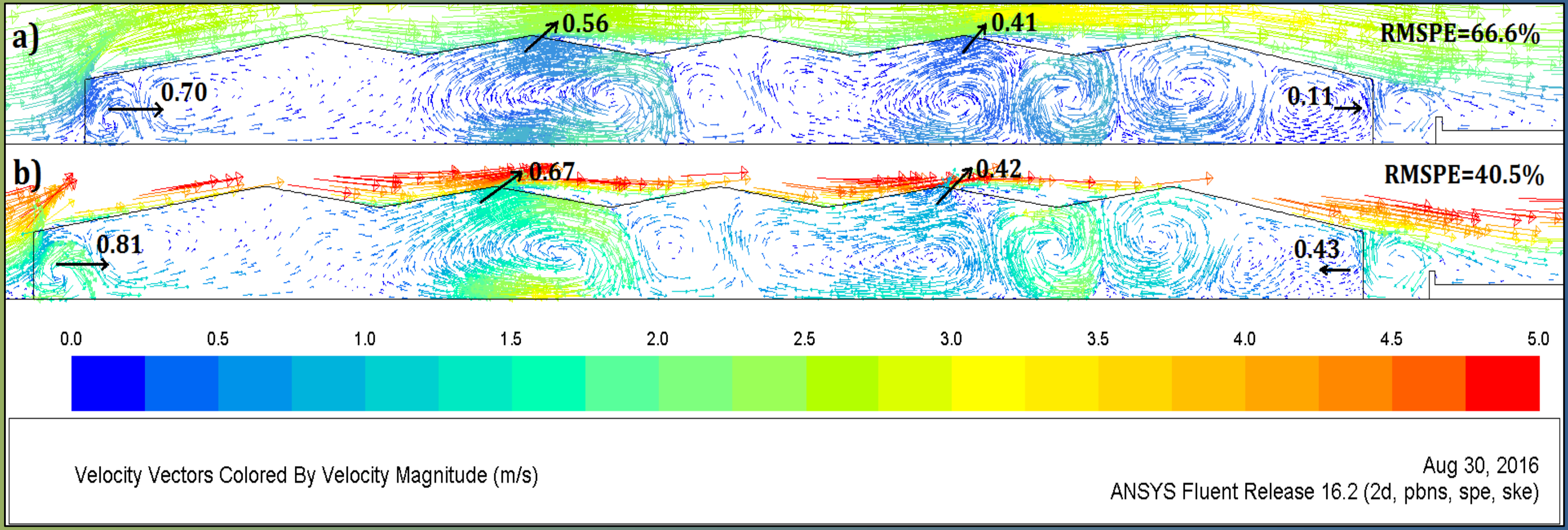
K=0.94, α_L=8.6×10^{-6} (g CO_2 J^{-1}), a_A=8.5×10^{-5} (m^{-3} J^{-1}), b_A=0.021 (m^2 s J^{-1}) m=0.1 (Acock *et al.*, 1978; Nederhoff and Vegter, 1994a).



Results and discussion

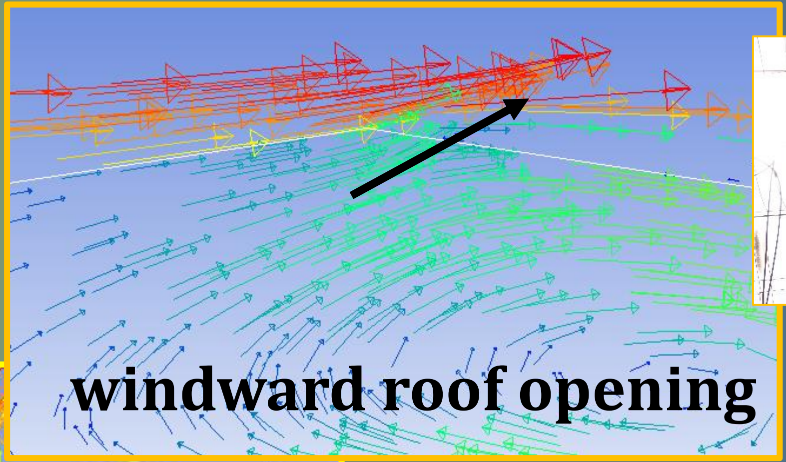
Airflow patterns

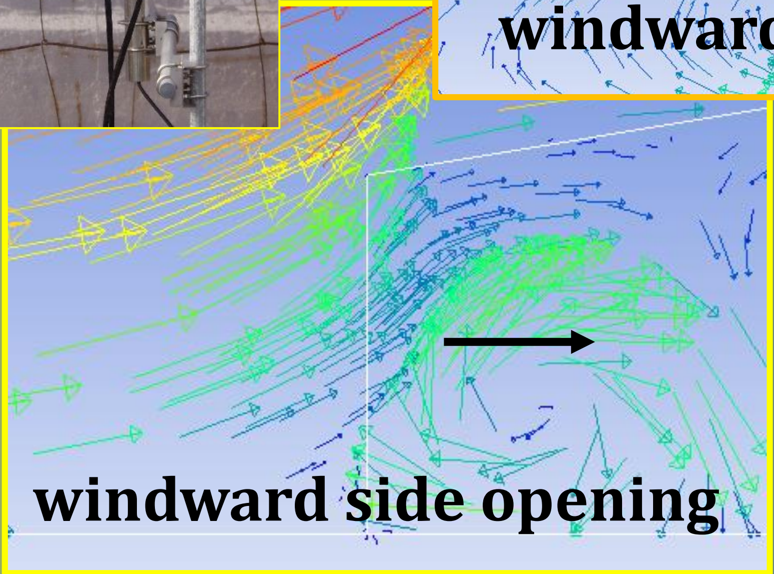
A good agreement can be observed between the simulated airflow and the velocities measured in the greenhouse openings with the anemometers.

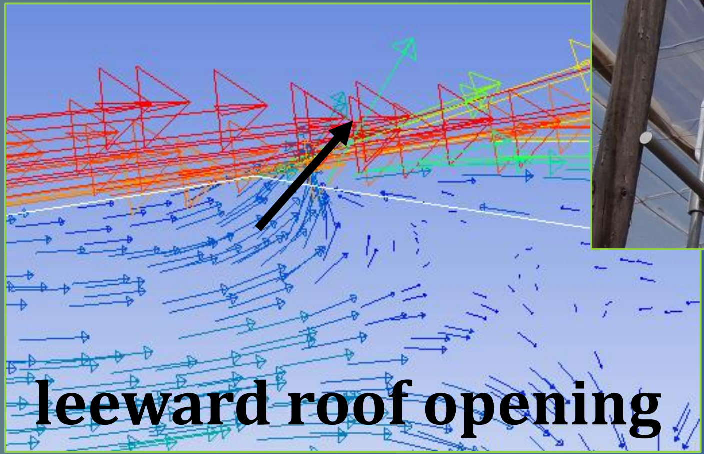


Airflow patterns

Outside air entered the greenhouse through the windward side openings exiting by the two roof vents.







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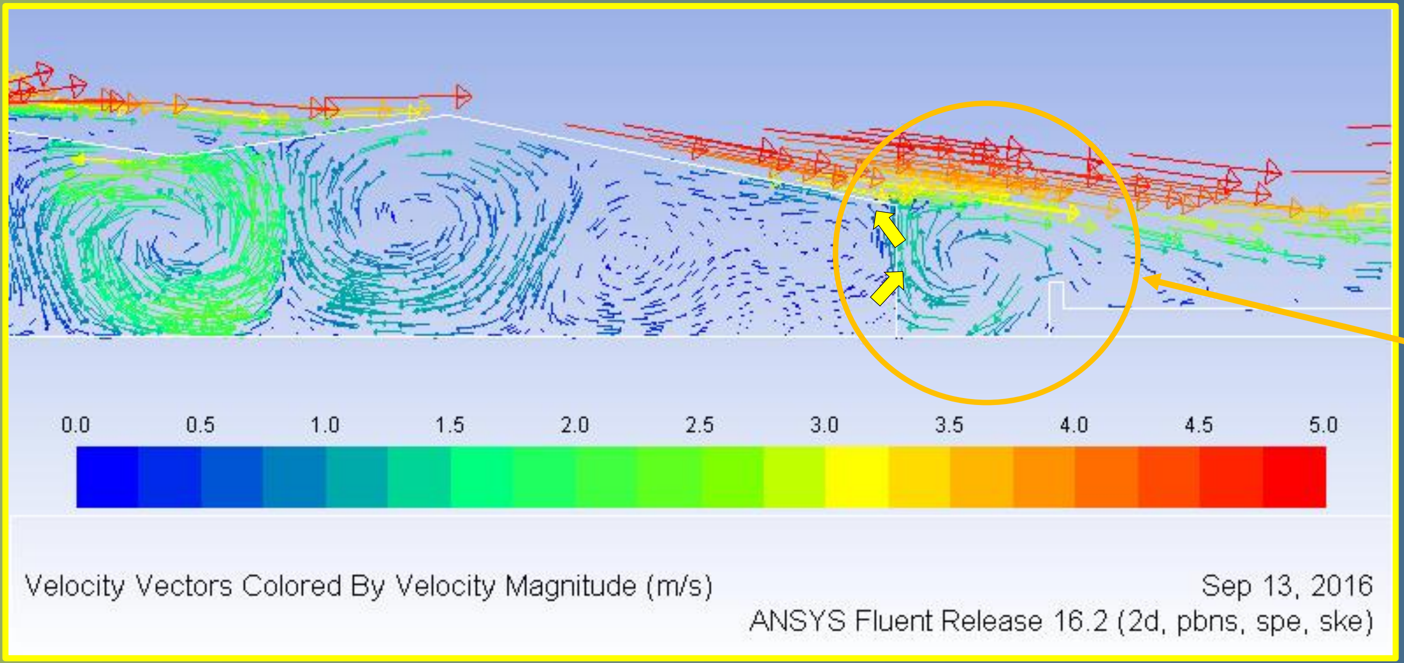
Airflow patterns

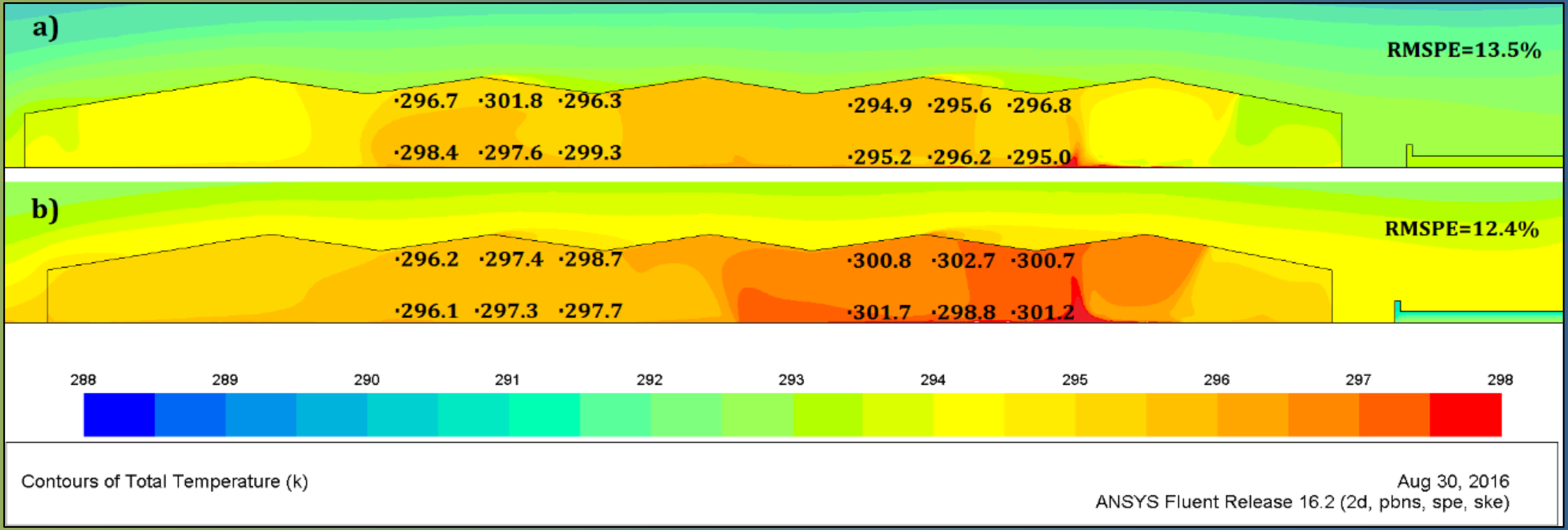
In both simulations, a vortex was observed between the leeward side wall and the road, located at 2.2 m of the wall.



As consequence of this vortex, air entered and exited through the leeward side vent with a low velocity.

Temperature distributions

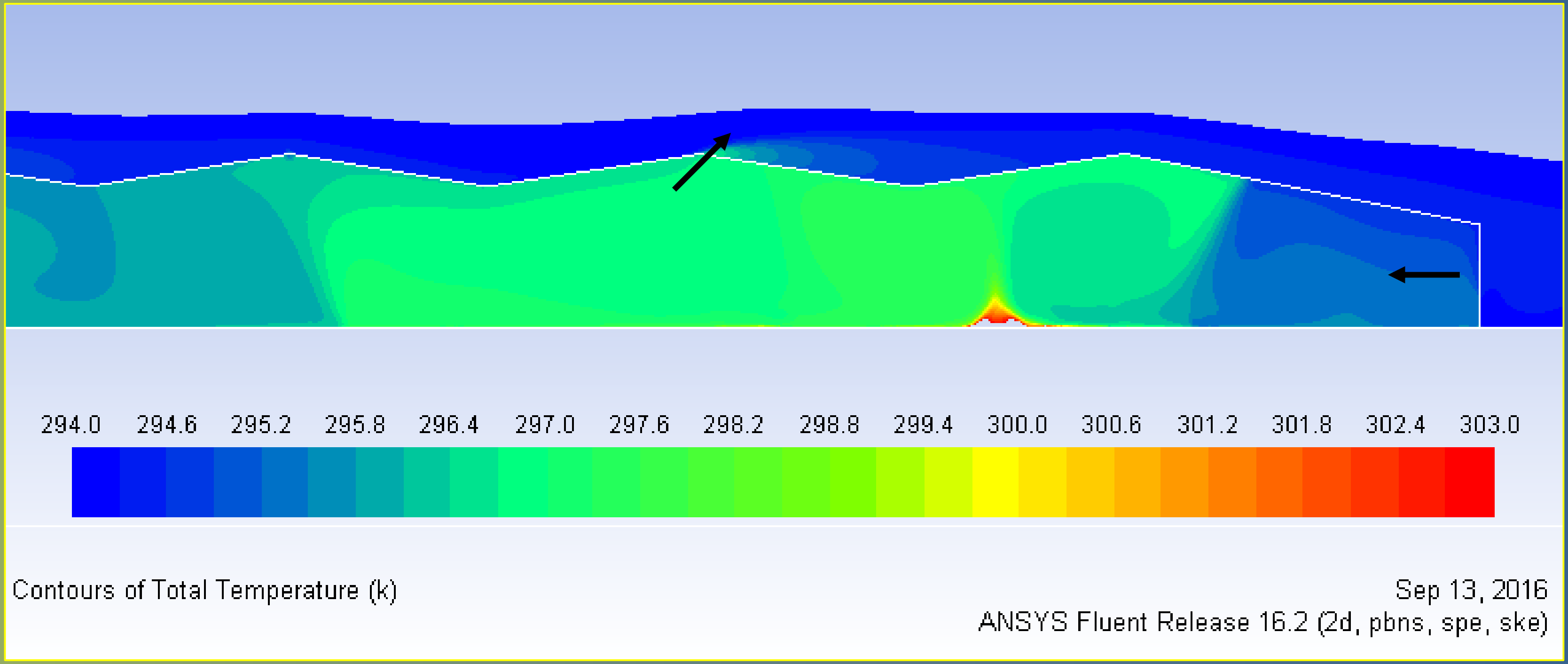
The simulated temperature distributions show the entrance of outside cold air by the windward side opening.



Temperature distributions

Results and discussion

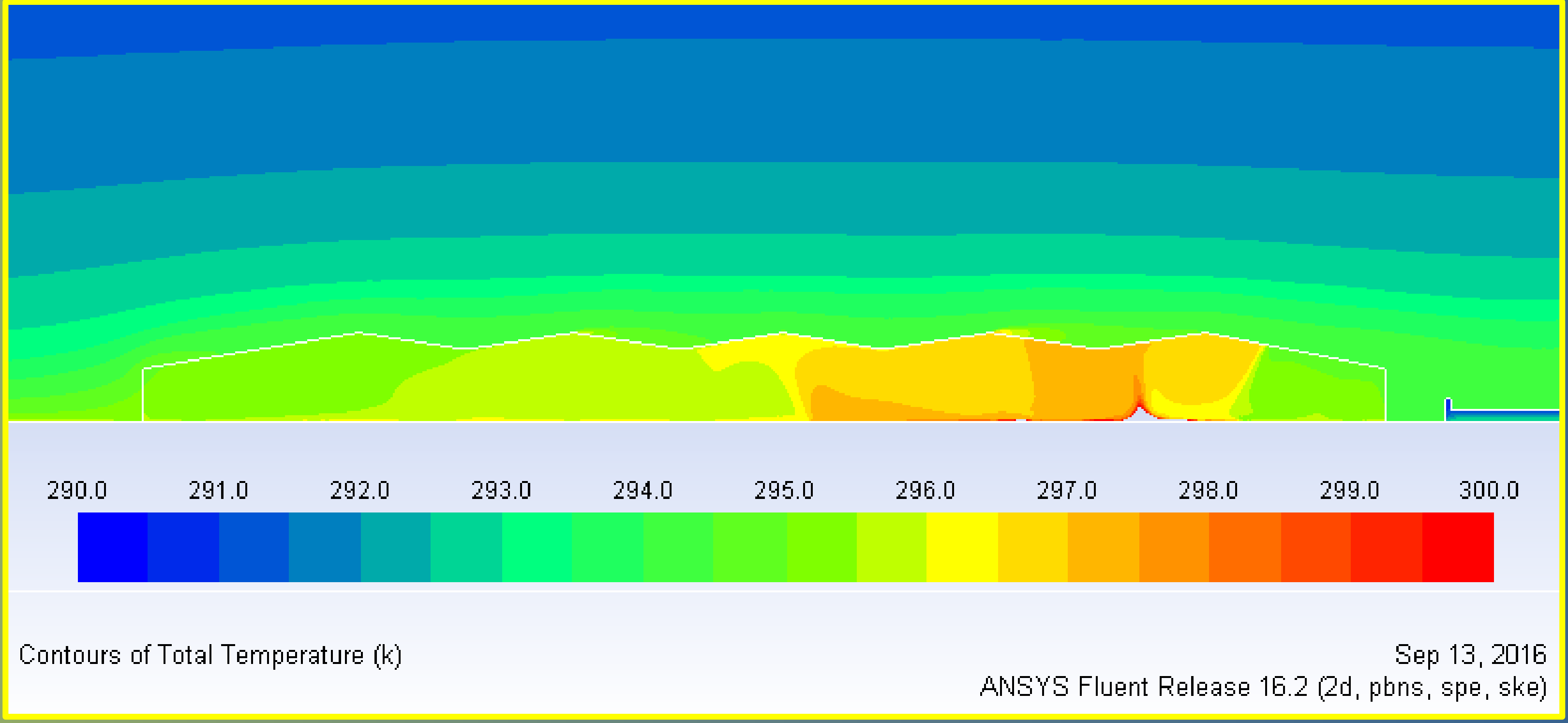
The warm air exited the greenhouse through the two roof vents, observing the higher temperatures below the leeward roof opening located in the fourth span.



Temperature distributions

Results and discussion

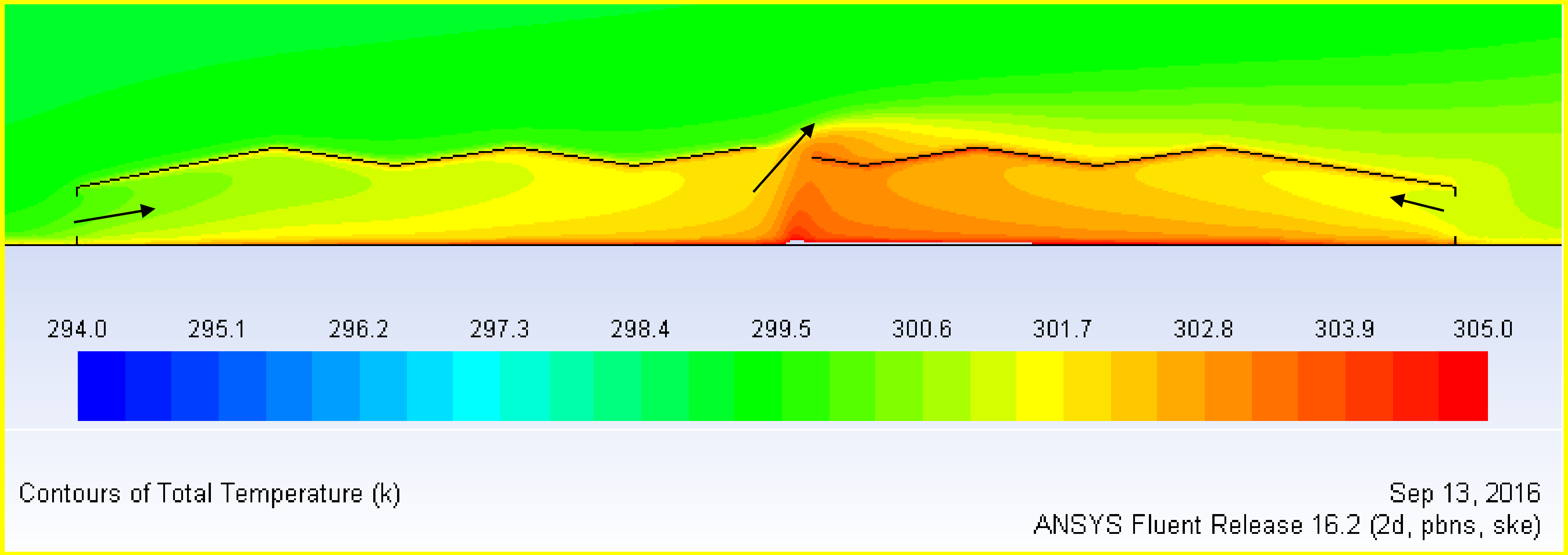
Due to the little effect of the plant cooling, resulting of the low crop development (L_{AI}=0.29 m^2 m^{-2}) and the reduced surface occupied in the greenhouse (35% of the ground surface), inside air was until 10 ºC hotter than outside air.



Temperature distributions

Results and discussion

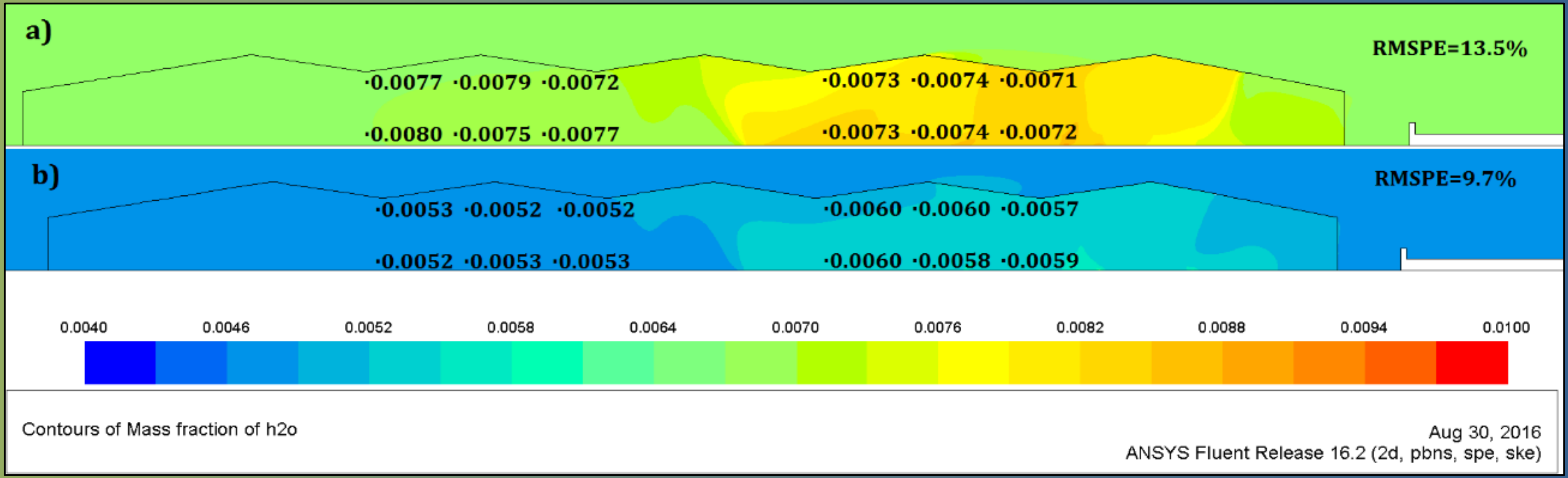
The greater temperature of the leeward part of the greenhouse, produced by the lower ventilation, was observed (experimentally and with CFD simulations) in a previous work (Molina-Aiz *et al.*, 2004) in the same experimental greenhouse but with only a central roof vent.



Humidity distributions

Results and discussion

Simulations showed an increase of humidity in the area occupied by the crop as consequence of the plants transpiration included in the CFD model.



Measured data the first day showed higher humidity in the windward part of the greenhouse than in the leeward part.

This humidity distribution can be produced by evaporation from the soil after irrigation.

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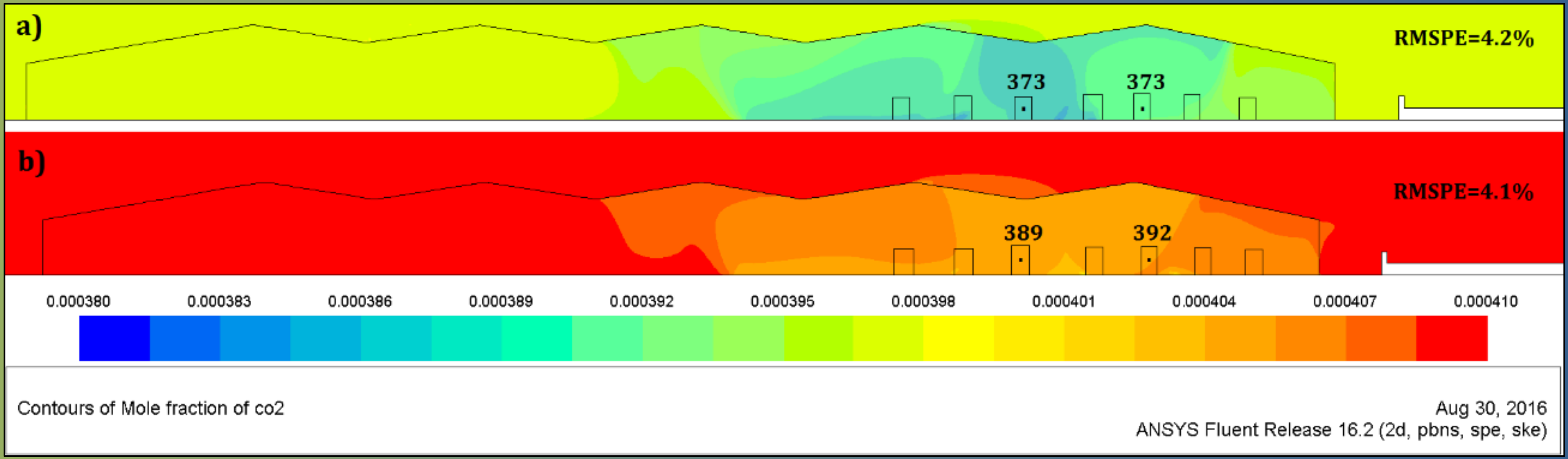
CO_2 distribution

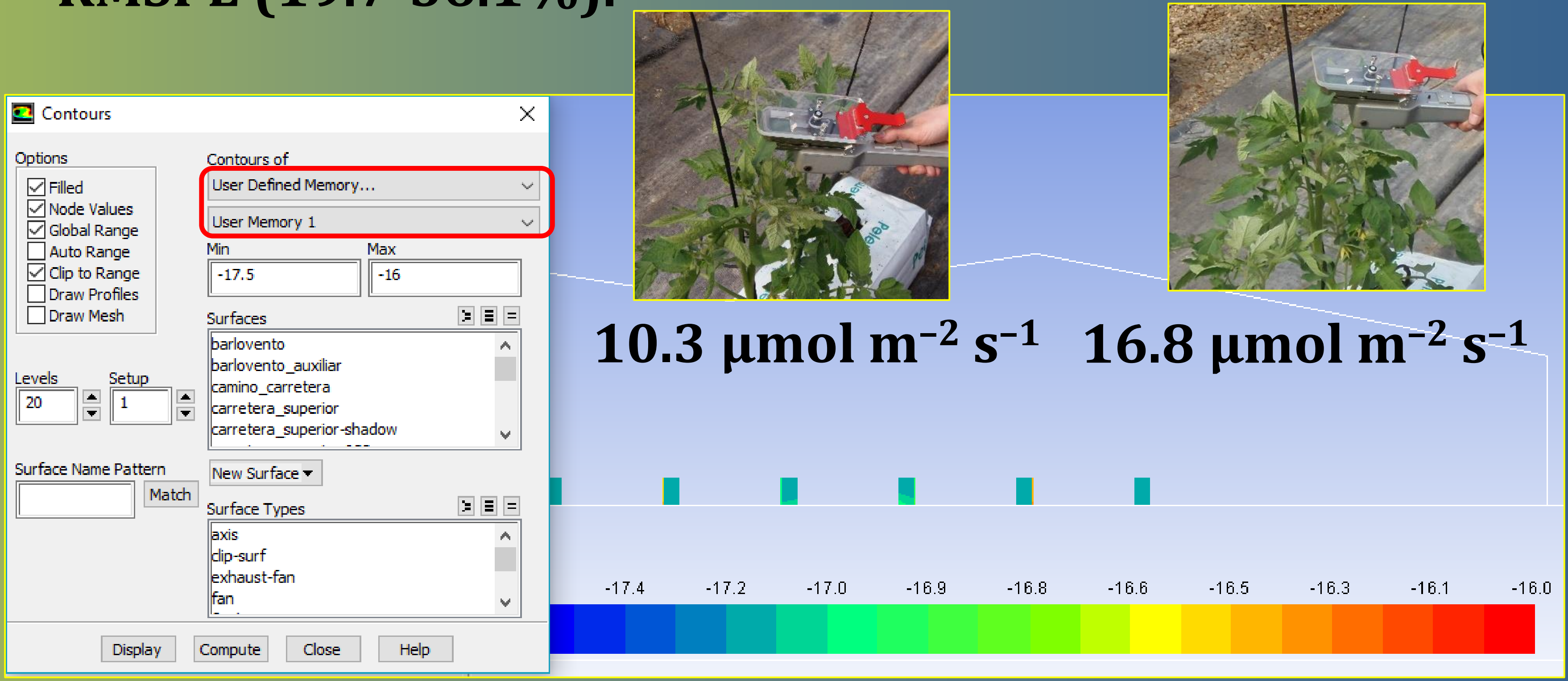
Simulations of CO_2 distribution show a reduction of the concentration in the leeward part of the greenhouse where the plants absorb the gas by photosynthesis.

This reduction was very weak due to the low development of the crop at the moment of measurements (L_{AI}=0.29 m^2 m^{-2}).



Crop photosynthesis

The great variability of measured values of photosynthesis inside the crop canopy (differences of 47.9% between rows) resulting in greater values of RMSPE (19.7-36.1%).



10.3 µmol m^{-2} s^{-1} 16.8 µmol m^{-2} s^{-1}

Crop photosynthesis

These values of photosynthesis (1.6-2.8 gCO_2 m^{-2}leaf h^{-1}) were similar to the values of 2.9 gCO_2 m^{-2}leaf h^{-1} measured in plants of tomato growing inside a Venlo-type glasshouse by Nederhoff and Vegter (1994a).

The measured values also agreed with the net photosynthesis of 10-15 µmol m^{-2}leaf s^{-1} reported by Ayari *et al*. (2000) for tomato crop inside a four-span arched greenhouse and by Shibuya *et al*., (2006) for tomato seedlings in a growth chamber.

Conclusions

From validation of the developed CFD model of a naturally ventilated Almería-type greenhouse with a tomato crop inside, we can conclude that plants photosynthesis can be simulated accurately with CFD including a user-defined function (UDF) in the numerical model.

Values of simulated net photosynthesis agree with the measured in the experimental greenhouse and with the values reported in bibliography.


Thank you

Literature Cited

Acock, B., Hand, D.W., Thornley, J.H.M., and Warren Wilson, J. (1976). Photosynthesis in stands of green peppers. An application of empirical and mechanistic models to controlled-environment. Annals of Botany. *40*(170), 1293–1307.

ANSYS (2013). ANSYS Fluent Theory Guide. Release 15.0. ANSYS, Inc., Canonsburg (USA), 814 pp.

Ayari, O., Dorais, M., and Gosselin, A. (2000). Daily variations of photosynthetic efficiency of greenhouse tomato plants during winter and spring. J. Amer. Soc. Hort. Sci. *125*(2), 235–241.

Baeza, E.J., Pérez-Parra, J., and Montero, J.I. (2005). Effect of ventilator size on natural ventilation in parral greenhouse by means of CFD simulations. Acta Horticulturae. *691*, 465–472. http://dx.doi.org/10.17660/ActaHortic.2005.691.56

Bartzanas, T., Boulard, T., and Kittas, C. (2002). Numerical simulation of the airflow and temperature distribution in a tunnel greenhouse equipped with insect-proof screen in the openings. Computers and Electronic in Agriculture. *34*, 207–221. http://dx.doi.org/10.1016/S0168-1699(01)00188-0

Boulard, T., and Wang, S. (2002). Experimental and numerical studies on the heterogeneity of crop transpiration in plastic tunnel. Computers and Electronic in Agriculture. *34*, 173–190. http://dx.doi.org/10.1016/S0168-1699(01)00186-7

Bournet, P.E., and Boulard, T. (2010). Effect of ventilator configuration on the distributed climate greenhouses: A review of experimental and CFD studies. Computers and Electronics in Agriculture. *74*, 195–217. http://dx.doi.org/10.1016/j.compag.2010.08.007

Fatnassi, H., Boulard, T., and Bouirden, L. (2002). Simulation of air flux and temperature patterns in a large scale greenhouse equipped with insect proof nets. Acta Hortic. *578*, 329–338. http://dx.doi.org/10.17660/ActaHortic.2002.578.41

Fatnassi, H., Boulard, T., and Lagier, J. (2004). Simple indirect estimation of ventilation and crop transpiration rates in a greenhouse. Biosystems Eng. *88*(4), 467–478. http://dx.doi.org/10.1016/j.biosystemseng.2004.05.003

Fatnassi, H., Poncet, C., Bazzano, M.M., Brun, R., and Bertin, N. (2015). A numerical simulation of the photovoltaic greenhouse microclimate. Solar Energy. *120*, 575–584. http://dx.doi.org/10.1016/j.solener.2015.07.019

Haxaire, R. (1999). Caractérisation et modélisations des écoulements d'air dans une serre. (In French: Characterisation and modelling of air flows in a greenhouse). Ph. D. Thesis, Université de Nice Sophie Antipolis. Faculté des Sciences, France, 149 pp.

Kacira, M., Sase, S., and Okushima, L. (2004). Optimization of vent configuration by evaluating greenhouse and plant canopy ventilation rates under wind–induced ventilation. Transactions of the ASAE. *47*(6), 2059–2067. http://dx.doi.org/10.13031/2013.17803

Molina-Aiz, F.D., Valera, D.L., Peña, A.A., Gil, J.A., and López, A. (2009). A study of natural ventilation in an Almería-type greenhouse with insect screens by means of tri-sonic anemometry. Biosystem Eng. *104*(2), 224–242. http://dx.doi.org/10.1016/j.biosystemseng.2009.06.013

Molina-Aiz, F.D., Valera, D.L., and Álvarez, A.J. (2004). Measurement and simulation of climate inside Almería-type greenhouses using Computational Fluid Dynamics. Agricultural and Forest Meteorology. *125*, 33–51. http://dx.doi.org/10.1016/j.agrformet.2004.03.009

Literature Cited

Molina-Aiz, F.D., Valera, D.L., Álvarez, A.J., and Madueño, A. (2006). A wind tunnel study of airflow through horticultural crops: determination of the drag coefficient. Biosystem Eng. *93*(4), 447–457. http://dx.doi.org/10.1016/j.biosystemseng.2006.01.016

Molina-Aiz, F.D., Norton, T., López, A., Reyes-Rosas, A., Moreno, M.A., Marín, P., Espinoza, K., and Valera, D.L. (2016). Modelling of spatial variability of CO2 inside horticultural greenhouse with Computational Fluid Dynamic. Precision Agric. 26 pp. (In press). http://dx.doi.org/10.1007/s11119-015-xxxx-x

Monteith, J. L., & Unsworth, M. H. (2013). Principles of Environmental Physics Plants, Animals, and the Atmosphere. Fourth Edition. Elsevier Ltd., Oxford (UK), 401 pp.

Nederhoff, E.M., and Vegter, J.G. (1994a). Photosynthesis of stands of tomato, cucumber and sweet pepper measured in greenhouses under various CO_2 concentrations. Annals of Botany. *73*(4), 353–361. http://dx.doi.org/10.1006/anbo.1994.1044

Nederhoff, E.M., and Vegter, J.G. (1994b). Canopy photosynthesis of tomato, cucumber and sweet pepper in greenhouses: measurements compared to models. Annals of Botany. *73*(4), 421–427. http://dx.doi.org/10.1006/anbo.1994.1052

Okushima, L., Sase, S., and Nara, M. (1989). A support system for natural ventilation design of greenhouses based on computational aerodynamics. Acta Hortic. *284*, 129–136. http://dx.doi.org/10.17660/ActaHortic.1989.248.13

Ould Khaoua, S.A., Bournet, P.E., Migeon, C., Boulard, T., and Chassériaux, G. (2006). Analysis of greenhouse ventilation efficiency based on Computational Fluid Dynamics. Biosystems Engineering. *95*(1), 83–98. http://dx.doi.org/10.1016/j.biosystemseng.2006.05.004

Reichrath, S., Ferioli, F., and Davies, T.W. (2000). A simple computational fluid dynamics model of a tomato glasshouse. Acta Hortic. *534*, 197–204. http://dx.doi.org/10.17660/ActaHortic.2000.534.22

Roy, J.C., Pouillard, J.B., Boulard, T., Fatnassi, H., and Grisey, A. (2014). Experimental and CFD results on the CO2 distribution in a semi closed greenhouse. Acta Hortic. *1037*, 993–1000. http://dx.doi.org/10.17660/ActaHortic.2014.1037.131

Shibuya, T., Tsuruyama, J., Kitaya, Y. and Kiyota, M. (2006). Enhancement of photosynthesis and growth of tomato seedlings by forced ventilation within the canopy. Scientia Hortic. 109, 218–222. http://dx.doi.org/10.1016/j.scienta.2006.04.009

Tamimi, E., Kacira, M., Choi, C.Y., and An L., (2013). Analysis of microclimate uniformity in a naturally vented greenhouse with a high-pressure fogging system. Transaction of the ASABE. *56*(3), 1241–1254. http://dx.doi.org/10.13031/trans.56.9985

Teitel, M. (2013). Flow through concertina-shape screens. Biosystems Engineering. *116*, 155–162. http://dx.doi.org/10.1016/j.biosystemseng.2013.07.015

Thornley, J.H.M. (1976). Mathematical models in plant physiology. Academic Press, London, UK, 331 pp.

Valera, D.L., Belmonte, L.J., Molina-Aiz, F.D., and López, A. (2016). Greenhouse agriculture in Almería. A comprehensive techno-economic analysis. Cajamar Caja Rural, Almería (Spain). 504 pp.