UNIVERSIDADE DE ÉVORA

# Modelling the Climate in Unheated Tomato Greenhouses and Predicting *Botrytis cinerea* Infection

Thesis submitted for the degree of Doctor of Rural Engineering by

**Fátima de Jesus Folgôa Baptista**

**Supervisor: Doctor Bernard John Bailey**

**Co-Supervisor: Professor Jorge Ferro Meneses**

**Esta tese não inclui as críticas e sugestões feitas pelo júri.**

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## Abstract

*Botrytis cinerea* Pers.: Fr. is the causal agent of grey mould disease and is one of the most important diseases affecting tomato crops in unheated greenhouses. Ventilation is the technique used for environmental control in Mediterranean unheated greenhouses. Many growers tend to restrict nocturnal ventilation in order to increase air temperature, forgetting that humidity is a very important factor affecting plant development and most of all that high humidity is favourable to fungal disease development.

Growers usually apply large quantities of chemical fungicides with disadvantages such as commercialization problems due to chemical residues on tomato fruits, high production costs, risk of fungicide resistance and negative environmental impacts. Nocturnal (or permanent) ventilation is an effective way to reduce high relative humidity inside greenhouses and could be a useful tool to minimise chemical use in unheated greenhouses.

The main purpose of this research was to study the effect of nocturnal ventilation on *B. cinerea* occurrence in unheated tomato greenhouses and to develop a disease predictive model. Experiments were carried out at the Instituto Superior de Agronomia in Lisbon in two identical adjacent double-span greenhouses. The structural material was galvanized steel and the covering material was a three layer co-extruded film. Each greenhouse had a floor area of 182 $m^2$, eaves height of 2.8 m and ridge height of 4.1 m; the orientation was north-south. The climate was controlled by natural ventilation, using continuous apertures located on the roof and side walls over the entire length of the greenhouses. Two different natural ventilation treatments were randomly assigned to the greenhouses. One treatment was permanent ventilation (PV), with the vents open during the day and night, while the other was classical ventilation (CV), in which the vents were open during the day and closed during the night.

A spring tomato crop (*Lycopersicon esculentum* Miller), cultivar *Zapata* was grown directly in the soil between the end of February and the end of July in both 1998 and 2000. The growing technique was the usual for greenhouse tomatoes in Portugal. Trickle ferti-irrigation tubes were located between each two rows of plants. Climatic data were measured with three meteorological stations, one located in the centre of each greenhouse and one outside. Air dry and wet bulb temperatures were measured using a ventilated psychrometer. Soil temperatures were recorded using thermistors, the leaf temperature was measured using infrared temperature thermometers and the cover

temperature was measured using a thermocouple attached directly to the inner film surface. Global and photosynthetically active (PAR) radiations, wind speed, soil moisture content and water draining from the lysimeter were also recorded.

All data were averaged and recorded on an hourly basis using two data logger systems from Delta - T Devices. Data on the evolution of the crop, such as plant growth, leaf area, flower production, fruit production, fruit weight and yield were also recorded. The number of leaflets with lesions caused by *B. cinerea* were counted and removed from the greenhouse from the randomly selected groups of plants, five times in 1998 and 10 times in 2000.

Experimental microclimate parameters recorded over the two years in the two greenhouses with different ventilation management are presented and analysed. It was shown that greenhouse air temperature was not significantly influenced by the night ventilation management. On the contrary, a significant reduction of air humidity occurred in the nocturnally ventilated greenhouse, even with unfavourable outside conditions that occurred during the spring of 2000.

A dynamic climate model was tested, modified step by step, parameterised and validated for the conditions which occurred during this research. The modifications were mainly related with the crop and the soil characteristics, the heat transfer coefficients and the ventilation sub-models. The good agreement between the predicted and measured data showed that the revised model can be used to estimate the greenhouse climate conditions, based on the weather conditions and on the greenhouse-crop system characteristics. Also, it was shown that the modifications to the original model improved its performance.

Nocturnal or permanent ventilation was shown to have a great contribution to reducing disease severity on tomato leaves caused by *B. cinerea*, in both years of the experiments. It was shown that nocturnal ventilation management is an environmental control technique which can be used as a prophylactic control measure, since it reduces the severity of *B. cinerea* on tomato crops grown in unheated greenhouses. This is a very important result since it permits a reduction in chemical use lowering both production costs and environmental impacts.

A model that predicts grey mould severity caused by *B. cinerea* on tomatoes grown in unheated greenhouses was developed as a function of the time duration with air temperature and relative humidity within certain ranges. This model was validated, and comparison between predicted and observed disease data showed good agreement.

Integration of the climate and the *Botrytis* models was tested and reasonable results were obtained, showing that integration of both models is possible. This combination permits the prediction of when the climate conditions would be favourable for disease development and what would be the expected grey mould severity. A warning system, defining disease risk levels based on disease severity was developed and could be a useful tool for technicians, advisors and growers, helping them to decide what are the adequate actions and the correct timing to avoid favourable conditions for disease development. A more practical and immediately implementable application was presented, defining disease risk levels based on the number of hours per day with relative humidity higher than 90%, which is a useful tool for growers, helping them to identify the risk of disease occurrence and making it possible to act in order to reverse or to avoid disease favourable conditions.

## Resumo alargado

Na Europa, a maior parte do tomate destinado ao consumo em fresco é produzido em estufas. Na zona Mediterrânica, a área de estufas aumentou significativamente nas últimas décadas, atingindo 144 000 ha em 1999, sendo a cultura do tomate uma das mais representativas. Nos Países Mediterrânicos as estufas são normalmente estruturas simples com cobertura de filme plástico e a ventilação natural é geralmente a técnica utilizada para controlar a temperatura e humidade no seu interior.

A *Botrytis cinerea* Pers.:Fr. é o agente causal da podridão cinzenta, doença responsável por elevados prejuízos na cultura do tomate em estufas não aquecidas. Esta doença pode ser responsável por perdas de produção na ordem de 20% e os tratamentos com fungicidas chegam a representar 60% do consumo total destes pesticidas ao longo de uma época de produção.

A podridão cinzenta contínua a ser uma doença de difícil controlo em estufas. De facto, não se conhecem cultivares de tomate que sejam naturalmente resistentes a este fungo e as condições ambientais nas estufas, a elevada densidade de plantas e o seu frequente manuseamento são factores que favorecem o seu desenvolvimento.

Os produtores, de modo a controlar a podridão cinzenta, recorrem frequentemente a aplicações de fungicidas quer directamente sobre a parte da planta infectada quer de forma generalizada em toda a cultura. A utilização frequente de fungicidas apresenta várias desvantagens, entre as quais se destacam: o aumento do risco de aparecimento de resistências, a existência de resíduos nos frutos que impedem a sua comercialização, o aumento dos custos de produção e os efeitos adversos no ambiente em geral. A ventilação nocturna é uma técnica de controlo ambiental que permite a redução da humidade no interior das estufas e que pode ser um meio adequado para minimizar a utilização de fungicidas em estufas não aquecidas.

O objectivo principal desta investigação foi estudar o efeito da ventilação nocturna na ocorrência de *B. Cinerea* na cultura de tomate em estufas não aquecidas na tentativa de encontrar uma solução sustentável que permita controlar a doença, reduzir a aplicação de fungicidas, diminuir os custos de produção e reduzir os efeitos negativos da utilização de pesticidas no ambiente. Para isso, foi definido um delineamento experimental que permitiu: 1. estudar a influência da ventilação nocturna nas condições ambientais nas estufas; 2. adaptar e validar um modelo climático para estufas não aquecidas; 3. estudar a influência da ventilação nocturna na ocorrência da podridão

cinzenta; 4. desenvolver e validar um modelo da *Botrytis* e 5. estudar a integração do modelo climático e do modelo da *Botrytis.*

O trabalho experimental foi realizado no Instituto Superior de Agronomia, em estufas não aquecidas entre Fevereiro e Julho de 1998 e de 2000. As estufas tinham uma área de 182 $m^2$ e o material de cobertura era filme plástico de camada tripla co-extrudido (Triclair). A orientação era Norte-Sul e a ventilação natural efectuava-se através de aberturas contínuas localizadas ao longo das paredes laterais e cobertura, ao longo de todo o comprimento da estufa. Os dois tratamentos relativos ao maneio da ventilação natural foram distribuídos ao acaso pelas estufas. Numa das estufas a ventilação foi permanente ou nocturna (PV), caracterizada pela abertura das janelas durante o dia e a noite enquanto na outra utilizou-se a ventilação clássica (CV), em que as janelas estavam abertas durante o dia e fechadas durante a noite.

A cultura instalada foi o tomate (*Lycopersicon esculentum* Miller), cultivar Zapata, plantado em linhas pareadas directamente no solo e conduzido a uma só haste. A densidade das plantas era de 2.6 plantas $m^{-2}$ e as técnicas culturais foram as usuais para a cultura do tomate em estufa em Portugal. Utilizou-se um sistema de rega gota-a-gota, com os tubos dispostos no centro das linhas de cultura pareadas.

Durante todo o ensaio foram recolhidas informações sobre: (i) as variáveis climáticas exteriores, como a temperatura de bolbo seco e de bolbo húmido, a radiação solar global e PAR, a velocidade do vento e a temperatura do solo; (ii) as variáveis climáticas interiores, como a temperatura de bolbo seco e de bolbo húmido, radiação solar global e PAR, a temperatura do solo a várias profundidades, a temperatura das folhas e a temperatura do material de cobertura. Os dados climáticos foram medidos com o auxílio de três estações meteorológicas, localizadas uma no interior de cada estufa e outra no exterior. Todos os dados foram registrados, após cálculo da média horária utilizando dois sistemas Data Logger, da Delta - T Devices.

Os dados relativos à evolução da cultura, tais como a área das folhas, a altura das plantas, a produção de flores e de frutos, o peso dos frutos e a produção total foram também registrados. Nas plantas representativas, selecionadas ao acaso, o número de folíolos com lesões causadas pela *B. cinerea* foram contados e removidos.

Os parâmetros climáticos recolhidos nas estufas ao longo dos dois anos de trabalho experimental são apresentados e analisados de forma a investigar o efeito da ventilação nocturna. Os resultados mostram que a temperatura do ar não foi afectada e que pelo contrário a humidade do ar foi significativamente reduzida mesmo com

condições meteorológicas adversas como as que ocorreram na Primavera de 2000, invulgarmente húmida. Este é sem dúvida um resultado muito importante que mostra como a ventilação nocturna pode ser usada sem causar problemas na cultura, já que não baixa a temperatura e apresenta resultados muito positivos no decréscimo da humidade, que se traduzem na diminuição da ocorrência de podridão cinzenta.

Um modelo climático dinâmico desenvolvido por Navas (1996) numa estufa Mediterrânea aquecida, com uma cultura de gérberas, foi testado, adaptado e validado para as condições especificas deste trabalho. Numa primeira fase foram identificados os ajustes necessários, essencialmente relacionados com os sub-modelos da ventilação, da resistência estomática e dos coeficientes de transferência de calor por convecção e também com as propriedades térmicas do solo. O modelo climático final incorpora expressões dos coeficientes de transferência de calor por convecção, determinados pela análise de dados experimentais registrados durante o ano de 2000. Os sub-modelos da ventilação e da resistência estomática foram selecionados da literatura da especialidade e são adequados às características da estufa e da cultura. A pesquisa bibliográfica mostrou enorme variabilidade nos valores obtidos por diversos autores, na caracterização das propriedades térmicas dos diferentes constituintes do solo, pelo que foram selecionados os valores que conduziram ao melhor ajustamento dos dados.

O modelo climático final foi validado com dados recolhidos em ambos os anos e os resultados da comparação entre valores previstos e medidos mostrou um bom ajuste. Este modelo pode ser utilizado para simular as condições ambientais no interior de estufas não aquecidas, com base nas condições meteorológicas e nas características da estufa e da cultura.

O número de folíolos com lesões causadas pela *B. cinerea* foram quantificados de forma a estudar a influência da ventilação nocturna na ocorrência da podridão cinzenta no tomate em estufas não aquecidas. Verificou-se que esta técnica permite reduzir significativamente a severidade e incidência da doença. Este resultado foi ainda mais interessante devido às diferentes condições climáticas verificadas nos dois anos de trabalho experimental. De facto, mesmo com uma primavera húmida, como a de 2000, foi possível reduzir significativamente o número de lesões causadas pela *B. cinerea* na estufa ventilada durante a noite. Assim, a ventilação nocturna pode ser usada como medida profilática.

Foi desenvolvido um modelo (BOTMOD) que permite prever a severidade da doença em função do tempo em que as condições de temperatura e humidade relativa se

encontram em determinados valores. Este modelo foi validado e a comparação entre dados previstos e observados mostrou um bom ajuste. A integração deste modelo com o modelo climático permite prever quando as condições ambientais serão favoráveis para o desenvolvimento da doença e qual a severidade esperada.

Foi desenvolvido um sistema de aviso, a partir de níveis de risco da doença, com base na severidade, e que poderá vir a constituir uma ferramenta útil para técnicos e produtores, na tomada de decisão sobre as medidas de controlo e o momento de agir para evitar as condições favoráveis ao desenvolvimento da doença. Foi também apresentado um resultado mais prático e de possível aplicação imediata pelos produtores, definindo níveis de risco em função do número de horas por dia em que a humidade relativa é maior que 90%, mas que facilmente pode ser adaptado a outros valores. Hoje em dia, na maioria das estufas comerciais a temperatura e a humidade relativa são parâmetros monitorizados e aplicando um sistema simples como o proposto é possível prever o nível de risco para a ocorrência da doença, por forma a actuar de modo a reverter ou mesmo a evitar as condições favoráveis. Este procedimento contribuirá para reduzir o número de tratamentos com fungicidas, com evidentes vantagens econômicas e ambientais.

A hipótese de que a ventilação nocturna pode reduzir a humidade nas estufas, reduzindo assim a ocorrência de podridão cinzenta e logo a utilização de fungicidas foi confirmada. No entanto, um controlo eficiente desta doença só é possível através de um sistema integrado recorrendo a todas as medidas disponíveis, sejam de controlo ambiental, cultural, biológico e por vezes químico.

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# Notation

Symbol

| | |
|---|---|
| $A$ | area, $m^2$ |
| $b_1, b_2, b_3, m, n, p$ | constants |
| $c$ | specific heat, J $kg^{-1}$ $^oC^{-1}$ |
| $C$ | volumetric specific heat, J $m^{-3}$ $^oC^{-1}$ |
| $C_d$ | discharge coefficient, dimensionless |
| $C_d C_w^{0.5}$ | overall wind effect coefficient, dimensionless |
| $CV$ | classical ventilated greenhouse |
| $C_w$ | wind pressure coefficient, dimensionless |
| $dgm$ | deep growing medium |
| $DI$ | Disease Incidence |
| $ds$ | deep soil |
| $DS$ | Disease Severity |
| $e$ | vapour pressure, kPa |
| $e^*$ | saturated vapour pressure, kPa |
| $E$ | evapotranspiration, mg $m^{-2}$ $s^{-1}$ |
| $g$ | acceleration of gravity, m $s^{-2}$ |
| $Gr$ | Grashof number |
| $h$ | vertical distance between roof and side vents, m |
| $H$ | vertical height of the opening, m |
| $h_c$ | convection heat transfer coefficient, W $m^{-2}$ $^oC^{-1}$ |
| $i$ | enthalpy, J $kg^{-1}$ |
| $IP$ | number of infected plants |
| $k$ | thermal conductivity, W $m^{-1}$ $^oC^{-1}$ |
| $K_{SR}$ | extinction coefficient |
| $l$ | characteristic dimension of the surface, m |
| $LAI$ | leaf area index |
| $Le$ | Lewis number |
| $ME$ | mean error |
| $MSE$ | mean square error |
| $MST$ | total variance |

| | |
|---|---|
| $n$ | number of observations |
| $Nu$ | Nusselt number |
| $P$ | Pressure, Pa |
| $Pr$ | Prandtl number |
| $PV$ | permanent ventilated greenhouse |
| $Q$ | heat flux, W $m^{-2}$ |
| $Q_C$ | heat exchange through the cover, W $m^{-2}$ |
| $Q_m$ | heat storage (or extraction), W $m^{-2}$ |
| $Q_{SRi}$ | solar radiation heat gain, W $m^{-2}$ |
| $Q_{ve\_la}$ | latent heat losses due to ventilation, W $m^{-2}$ |
| $Q_{ve\_se}$ | sensible heat losses due to ventilation, W $m^{-2}$ |
| $r_e$ | external resistance, s $m^{-1}$ |
| $Re$ | Reynolds number |
| $RH$ | relative humidity, % |
| RH85 | Cumulative hours with RH > 85% |
| RH90 | Cumulative hours with RH > 90% |
| RH7075 | Cumulative hours with RH between 70 and 75% |
| RH8590 | Cumulative hours with RH between 85 and 90% |
| RH9095 | Cumulative hours with RH between 90 and 95% |
| $r_i$ | stomatal resistance, s $m^{-1}$ |
| $r_a^2$ | Adjusted determination coefficient |
| $RMSE$ | root mean square error |
| $sd$ | standard deviation |
| $se$ | standard error |
| $SR$ | solar radiation, W $m^{-2}$ |
| $t$ | temperature, ºC |
| $t_i$ | temperature at layer i (i = 1→ 5), ºC |
| t8 | Cumulative hours with temperature < 8ºC |
| t10 | Cumulative hours with temperature < 10ºC |
| t15 | Cumulative hours with temperature > 15ºC |
| t20 | Cumulative hours with temperature > 20ºC |
| t25 | Cumulative hours with temperature > 25ºC |
| t810 | Cumulative hours with temperature between 8 and 10ºC |
| t1015 | Cumulative hours with temperature between 10 and 15ºC |
| t1520 | Cumulative hours with temperature between 15 and 20ºC |

| | |
|---|---|
| t2025 | Cumulative hours with temperature between 20 and 25ºC |
| $T$ | temperature (Kelvin) |
| $TOP$ | total number of observed plants |
| $V$ | ventilation rate, $m^3\ s^{-1}$ |
| $v$ | air speed, $m\ s^{-1}$ |
| $VPD$ | vapour pressure deficit, kPa |
| $v_w$ | wind speed, $m\ s^{-1}$ |
| $w$ | absolute humidity, $kg\ kg^{-1}$ |
| $x_{wa}$ | moisture content, $cm^3\ cm^{-3}$ |
| $\bar{x}$ | Mean |
| $y_i$ | observed value |
| $y_i'$ | predicted value |
| $z$ | depth, m |
| $\upsilon$ | kinematic viscosity, $m^2\ s^{-1}$ |
| $\gamma$ | psychrometric constant, Pa $ºC^{-1}$ |
| $\kappa$ | thermal diffusivity, $m^2\ s^{-1}$ |
| $\beta$ | thermal expansion coefficient, $K^{-1}$ |
| $\sigma$ | Stefan-Boltzman constant, $5.67 \times 10^{-8}$, $W\ m^{-2}\ K^{-4}$ |
| $\tau$ | transmissivity, dimensionless |
| $\alpha$ | absortivity, dimensionless |
| $\rho$ | density, $kg\ m^{-3}$ |
| $\varepsilon$ | emissivity, dimensionless |
| | factor relating roof and side areas, dimensionless |
| $\lambda$ | latent heat of vaporization, $J\ kg^{-1}$ |
| $\alpha, \beta$ | evapotranspiration coefficients, dimensionless |
| $\vartheta_{SR}$ | diffusion coefficient, dimensionless |
| $\Delta P$ | pressure difference, Pa |
| $\Delta t$ | temperature difference, ºC |
| $\varphi$ | reflectivity, dimensionless |
| $\xi$ | resistance of the opening, dimensionless |

Subscripts

| | |
|---|---|
| $c$ | convection |
| $co$ | cover |

| | |
|---|---|
| *con* | condensation |
| *cr* | crop |
| *d* | dew point |
| *ev* | evaporation |
| *f* | forced |
| *g* | ground |
| *gm* | growing medium |
| *i* | inside |
| *ia* | inside air |
| *k* | conduction |
| *la* | latent heat |
| *m* | mixed |
| *n* | natural |
| *o* | outside |
| *oa* | outside air |
| *p* | heating pipes |
| *R* | roof |
| *r* | thermal radiation |
| *S* | side |
| *s* | soil |
| *se* | sensible heat |
| *SR* | solar radiation |
| *surf* | surface |
| *t* | thermal buoyancy |
| *tr* | transpiration |
| *ve* | ventilation |
| *w* | wind |
| *wa* | water |

# 1. Introduction

## 1.1 Definition of the problem

Tomato is one of the most important greenhouse crops; most of the fresh tomatoes marketed in the European Union are produced as protected crops. Greenhouse areas in Mediterranean regions have increased during the last decades, reaching 144,000 ha in 1999, with tomato being the most commonly grown vegetable (Castilla, 2002). Mediterranean greenhouses are very different from those used in Northern countries. In the North most greenhouses are heated and covered with glass as a way to maximise solar radiation gain. In the South, where the air temperature is warmer and solar radiation is considerable higher, greenhouses are usually not heated and are covered with plastic films. Environmental control in such greenhouses is essentially achieved using various ventilation techniques to control temperature and humidity.

*Botrytis cinerea* Pers.: Fr. is the causal agent of grey mould disease and is one of the most important diseases affecting tomato crops in unheated greenhouses, where it usually primarily infects the leaves. This disease could be responsible for production losses of 20% and fungicide treatments against *B. cinerea* could represent about 60% of the total fungicides used over a cropping season (Prieto *et al*., 2003).

Grey mould remains a fungal disease of greenhouse tomatoes that is very difficult to control. Natural resistance to this fungus has not been found in cultivated tomato plants (Elad *et al*., 1996; Nicot and Baille, 1996) and tomato production in greenhouses provides the ideal environment for fungal diseases. The warm, humid environment, high plant density and frequent handling are conducive to the establishment and spread of the pathogen.

High relative humidity and the presence of free water on the plant surfaces have been recognized as favourable to the development of grey mould. Recommendations to growers for avoidance of the disease include ventilation and heating of the greenhouses to reduce relative humidity and to avoid condensation. However, most greenhouse climate control is related to air temperature, since growers feel that this is the most important climatic factor which influences the crop productivity. It is very common during the winter period to find greenhouses completely closed during the night as a way to reduce heat losses, forgetting that humidity is also a very important factor which affects plant development and that most of all high humidity is favourable to disease

development. One of the major reasons to control humidity is the avoidance of *B. cinerea* disease.

Due to the common occurrence of grey mould, its potentially high rate of spread and high production losses it causes, growers usually apply large amounts of chemical fungicides to protect their crops. This practice may lead to chemical residues on tomato fruits which impede the commercialization, increase production costs and increase the risk of developing fungicide resistances (Abreu *et al.*, 1994).

According to FRAC (1998) resistance to benzimidazoles (carbendazime, benomyl) were described for the first time in 1969-1970 and to the dicarboximides (iprodione) in 1982 in grape grey mould. Resistance to fungicides is a normal phenomenon embodied in the natural process of evolution of biological systems and *B. cinerea* is a pathogen that easily develops resistance to fungicides, which is particularly true in Mediterranean areas where vegetables like cucumbers and tomatoes are grown under plastic films. Once it arises, resistance is inherited, since it results from one or more changes in the genetic constitution of the pathogen population. Brent (1995) summarised the main recommended strategies to avoid fungicide resistance as: the avoidance of repetitive and sole use, mix or alternate chemical fungicides with different mode of action, limit the number and timing of treatments, maintain recommended doses and integration with non-chemical methods.

Environmental and health concerns have increased public attention and pressure to reduce chemicals use in agriculture over the last decade. The European Commission in a communication to the European Parliament in 2002 encourages agricultural practices that reduce or eliminate pesticide use. In response to this communication the Parliament recommended a 50% reduction in the use of these chemicals over 10 years (Resolution of the European Parliament 2002/2277(INI)).

In addition to public and political pressures and the risk of fungicide resistance, only a few fungicides are now labelled for use in greenhouse tomatoes, and their high costs, have encouraged growers and scientists to find alternative methods to manage grey mould for sustainable and profitable greenhouse tomato production. At the present time, sustainability – economic, technical and environmental – is becoming the primary aim of modern agriculture. Integrated Pest Management combines biological, cultural, environmental and chemical tools in a way that minimizes economic, health and environmental risks. It uses all types of countermeasures against crop disease such as the use of resistant crop varieties, biological control agents, appropriate hygienic

practices, like crop rotation and removal of diseased parts of plants and avoidance of climatic conditions favourable to the development of the pathogen, by adequate control of ventilation and heating systems. A strong reduction in pesticides consumption could be achieved by using an Integrated Pest Management, which would be strongly encouraged for a sustainable greenhouse management (Castilla *et al.*, 2004).

It is consensual that it is not possible to control grey mould only with fungicides and a global cultural strategy is necessary. This is a typical situation where one single control method may not be efficient and an integrated approach has to be taken (Nicot and Baille, 1996). Some greenhouse tomato producers are already practicing alternative methods for disease management that reduce the need for fungicides. These strategies include the use of hot water lines between the plants, which warms the foliage contributing to drying it, deleafing to remove infected leaves, and improving the air circulation near the moist soil and floor.

Environmental control techniques such as adequate ventilation and air temperature management may control the psychrometric characteristics of the greenhouse and reduce high relative humidity levels, reducing leaf wetness duration and contribute to the minimization of the occurrence of the fungus. Some researchers have been dedicated to study biological control of plant pathogens (Elad *et al.*, 1996). Some antagonists are now available in the market, such as *Streptomyces griseovirides* strain K61 (AgBio Development o., Westminster, CO) and *Trichoderma harzianum* Rifai strain 1295-22 (BioWorks, Inc, Geneva, NY). Lamboy *et al*. (2006) mentioned that some biological control products are promising in greenhouse tomato production.

However, chemical control methods will remain an option to maintain reliable crop yields of good quality, but it is possible to minimise their use and maybe to avoid it depending on the combination of the production factors, such as crop practices, external climatic conditions and the environmental control techniques used. Utilisation of climate management for disease control is increasingly regarded by tomato growers as one of the most efficient tools against *B. cinerea*.

Nocturnal (or permanent) ventilation offers a great potential for the control of humidity dependant diseases in greenhouse vegetables in the Mediterranean regions. Furthermore, this does not imply great changes in cropping practices, which could facilitate their adoption by the growers, as well as the integration with other control methods. In Mediterranean greenhouses energy losses due nocturnal ventilation are not so important, and the nocturnal ventilation seems to be an interesting way of reducing

chemical applications. Studies by Meneses and Monteiro (1990), Meneses *et al.* (1994) and Baptista *et al.* (2001a) have shown that permanent natural ventilation is an effective way to reduce high relative humidity inside greenhouses and that it is the only option in non heated greenhouses.

The control of internal environmental conditions to avoid epidemics is a major concern of engineers and plant pathologists. Studying the environmental effects can help to clarify the conditions which prevent the fungal disease from developing during tomato growth and minimise the use of chemicals, which are expensive and can cause an environmental hazard. Disease infections and agro-meteorological variables can be related using simulation models that provide useful information to improve the timing of pesticide application.

Microclimatic parameters have been recognized as key factors in the development of diseases caused by fungal pathogens on aerial plant surfaces. The study of their effects has been used to develop risk prediction models and warning systems mainly for field crops in order to help the grower. In a greenhouse environment, the grower has some ability to intervene on the regulation of climatic parameters and the availability of epidemiological models can help and be useful to limit the occurrence of the conditions favourable to disease development.

Disease warning and integrated control systems are management decision aids that could help growers to apply chemicals more efficiently and economically than traditionally. It results in substantial reduction of spray frequency, which contributes to the reduction of the production costs, impact of pesticides in the environment and can delay the occurrence of fungicide resistance.

The more sophisticated facilities now being utilized for greenhouse crops have opened new opportunities for the control of diseases. Most commercial greenhouses are equipped with sensors to measure, at least, air temperature and relative humidity. With this information it is possible, using a warning system based on a disease risk level, to give to the growers the opportunity to act in time to reverse those conditions by using an appropriate environmental control technique, such as the increase of ventilation to promote the removal of water vapour.

The possibility of knowing the risk of disease development, provided by an epidemiological model integrated with a climatic model, which allows predicting humidity conditions, will be an important tool for helping growers in the decision process. This decision support system will allow predicting when the conditions will be

favourable to the disease development and will make it possible to act in a way to avoid those conditions.

## 1.2 Development of a hypothesis and objectives of the research

Since greenhouse climate parameters such as temperature and mainly humidity are recognized as some of the most important factors influencing the occurrence of *B. cinerea* disease in tomato crops and ventilation is the environmental control technique used to control those parameters in Mediterranean unheated greenhouses, the purpose of this research was to study the effect of ventilation management on the severity and incidence of this disease. In an attempt to reduce the occurrence of *B. cinerea* in tomato greenhouses, nocturnal ventilation was investigated under Mediterranean conditions in order to find the influence of the climate parameters on grey mould.

The hypothesis was formulated as: it would be possible to reduce greenhouse humidity by using nocturnal ventilation and would that contribute to the reduction of *B. cinerea* occurrence and the reduction of fungicide use? And if so, would it be possible to develop a model which could predict disease severity based on climate parameters?

In order to test this hypothesis, experiments were designed to give scientific knowledge about the influence of nocturnal ventilation on disease occurrence. For that it was important to record climate and disease information in greenhouses with different ventilation management. A tomato crop was grown in two identical greenhouses with the same cultural practices, but with different ventilation management: one greenhouse had nocturnal ventilation and the other classical ventilation.

The objectives of the research were:

1. To study the effect of nocturnal ventilation in the greenhouses climate parameters;
2. To adapt and to validate a dynamic greenhouse climate model for unheated tomato greenhouses;
3. To study the influence of nocturnal ventilation on the *B. cinerea* occurrence;
4. To develop and to validate a *Botrytis* model (BOTMOD) for unheated tomato greenhouses;
5. To study the integration of the climate and *Botrytis* models.

## 1.3 Outline of the thesis

The structure of the thesis was defined as a function of the above objectives. In Chapter 2 a general description of the experimental methods is presented, including the greenhouse-crop system and the measuring and recording equipment used over the two years of experiments. The experimental design is described, concerning the ventilation management and the disease assessment and statistical and modelling methodologies are explained.

Chapter 3 deals with the greenhouse environmental characteristics and is divided in two main parts: literature review and experimental results. In the first a review on the principles of natural ventilation is presented. In the second part the climate parameters recorded over the experiments are presented and analysed in order to study the effect of nocturnal ventilation. In Chapter 4 a brief review of the fundamentals of greenhouse climate and on climate modelling is presented and the adaptation and validation of a dynamic greenhouse climate model to the conditions of unheated tomato greenhouses is described.

In the Chapter 5, a brief literature review concerning *B. cinerea* fungus and the most important influencing factors is presented. The results of the disease observations are presented and the Disease Severity and Disease Incidence are analysed in order to investigate the influence of ventilation management on the occurrence of grey mould.

Finally, in Chapter 6 a *Botrytis* model (BOTMOD) is developed and validated for a tomato crop grown in unheated greenhouses. A brief review of the state of the art is presented. Based on the experimental results a disease risk level is defined and associated with Disease Severity, a warning system was developed as a way to help growers to decide when and how to act in order to avoid disease favourable conditions. Combination of climate and *Botrytis* models was performed and permits the prediction of when environmental conditions would be favourable for disease development and what would be the expectable severity.

Chapter 7 presents the final discussion and conclusions of the thesis and some suggestions for future work are presented.

# 2. General description of the experimental method

In this chapter the materials and methods used during the experimental work will be described. The field experiments were conducted in two unheated plastic greenhouses between the end of February and the end of July, during 1998 and 2000.

## 2.1 The experimental greenhouse system

### 2.1.1 The greenhouses

The experiments took place at the Instituto Superior de Agronomia in Lisbon (38º 42' N, 9º 11' W), where the climate can be characterised by moderate temperatures and relatively high humidity even during the summer periods. It is a Mediterranean climate with Atlantic influences (Ribeiro, 1987). Climatological data for Tapada da Ajuda (Lisbon), for the period between 1961 and 1990, are shown in Table 2.1 (IM, 2006).

Table 2.1 – Climatological data between 1961 and 1990 for Tapada da Ajuda (Lisbon) (IM, 2006)

| | February | March | April | May | June | July |
|---|---|---|---|---|---|---|
| Mean air temperature (ºC) | 11.9 | 13 | 14.4 | 16.6 | 19.6 | 21.8 |
| Maximum air temperature (ºC) | 15.7 | 17.5 | 19.1 | 21.9 | 25 | 27.6 |
| Minimum air temperature (ºC) | 8 | 8.5 | 9.6 | 11.4 | 14.1 | 15.9 |
| Relative humidity at 9 a.m. (%) | 82 | 77 | 74 | 71 | 70 | 67 |
| Relative humidity at 6 p.m. (%) | 77 | 71 | 69 | 67 | 64 | 60 |
| Solar radiation (hours) | 142.1 | 184 | 225.8 | 286.8 | 292.2 | 345.4 |
| Wind speed (m $s^{-1}$) | 2.1 | 1.8 | 1.8 | 1.9 | 1.9 | 2 |
| Number of days with precipitation > 0.1 mm | 13.7 | 11.2 | 11 | 7.1 | 4.9 | 1.1 |

The experiments were carried out in two identical adjacent double-span round arched greenhouses, as shown in Figures 2.1 and 2.2. The structural material was galvanized steel and the covering material consisted of a 200 μm thick three layer co-extruded film (Triclair). The external layers were low density polyethylene (PE) and internal layer was ethyl-vinyl-acetate (EVA). The film was stabilized with an anti-UV agent. The inside layer had an anti-drop treatment and the outside layer an anti-dust

treatment. The greenhouses were constructed at the beginning of 1998 and according to the manufacturer the co-extruded film was stabilised for a period of four years.

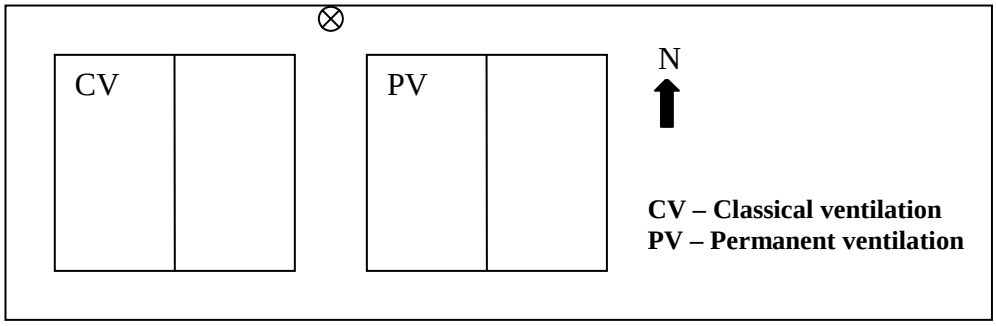
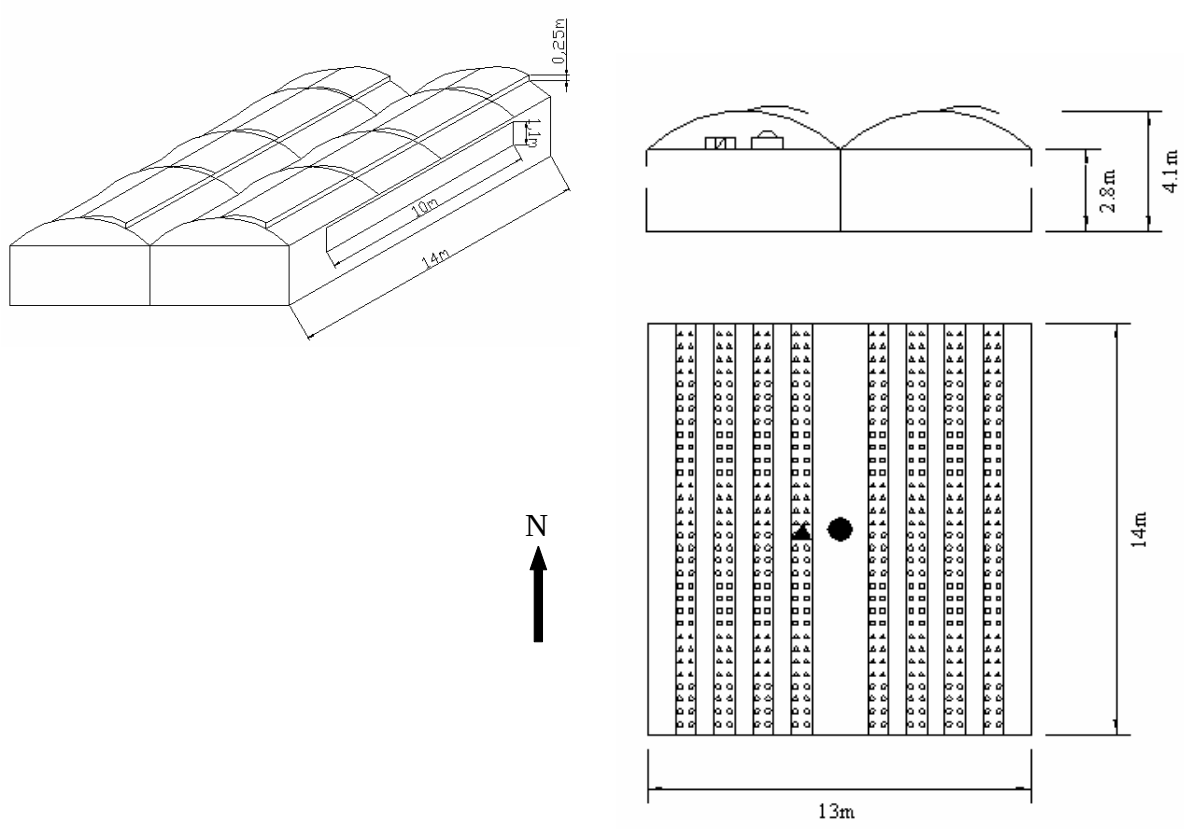



Figure 2.1 – Relative position of the greenhouses and location of the external weather station (⊗)




● Psychrometer (dry and wet bulb temperatures) ▲ Thermistors (soil temperature at different depths)
Pyranometer (PAR and Global radiation)

Figure 2.2 - Schematic perspective, section and plan of an experimental greenhouse and location of the sensors

Each greenhouse had a floor area of 182 $m^2$, eaves height of 2.8 m and ridge height of 4.1 m; the orientation was north-south. The climate was controlled by natural ventilation, using continuous apertures located on the roof and side walls over the entire

length of the greenhouses. Schematic drawings of an experimental greenhouse and the arrangement of the measuring equipment is shown in Figure 2.2. The surroundings were characterized by a forest on the north and west sides and an open field on the south and east sides.

The soil was a calcareous, red-brown clay soil (Cardoso, 1965). According to results of the analysis made in the Soil Physics and Agricultural Chemistry Laboratories of Évora University, the soil had a high phosphorous content (150 ppm), a very high potassium content (360 ppm), a pH (water) between 6.9 and 7.0, a bulk density of 1.28 g $cm^{-3}$ and 1.3 % organic matter content.

### 2.1.2 The tomato crop

A spring tomato crop (*Lycopersicon esculentum* Miller), cultivar *Zapata* from "Western Seed", was grown directly on soil between the end of February and the end of July in both 1998 and 2000. Before planting the soil was prepared and eight beds (0.85 m wide and 0.15 m high, separated by 0.70 m) were built along the greenhouses (Figure 2.3).

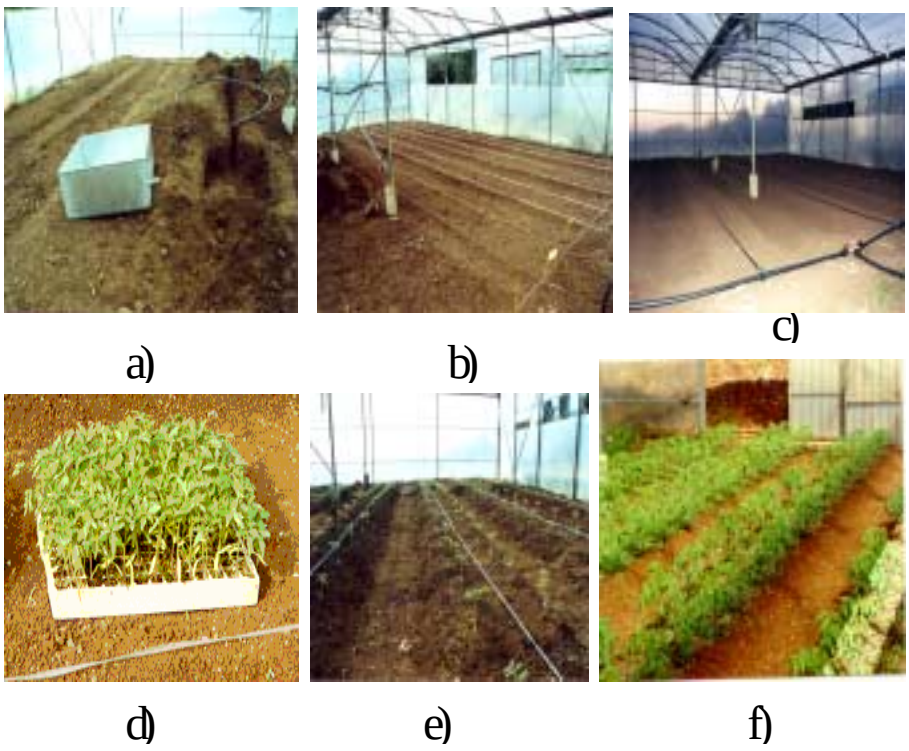



Figure 2.3 – Soil preparation and plant arrangement: a) lysimeter installation, b) beds preparation, c) irrigation system installation, d) young tomato plants in a plug tray, e) general view after plantation, f) general view two weeks after plantation

Young tomato plants were obtained from the nursery in plug trays and directly transplanted to the greenhouses soil during the third week of February in both experimental years. The tomato plants with 3-4 leaves were planted in twin rows (0.50 m × 0.50 m), giving a plant density of 2.6 plants $m^{-2}$. The growing technique was the usual for greenhouse tomatoes in Portugal, which meant the plants were trained to a single stem, pollination was by mechanical vibration of each inflorescence twice a week, pruned to 6 fruits per inflorescence and stopped by the second leaf above the seventh inflorescence. The plants were deleafed three times (12 May, 5 and 22 June in 1998 and 28 April, 8 and 26 June in 2000) to allow better air circulation between them, in accordance with normal horticultural practice, which meant that adjacent fruits were perfectly formed. Usually the leaves removed were senescent or had been attacked by fungi. Harvesting started in the last week of May and ceased at the end of July. Fruits were harvested when they were beginning to change colour, which meant that approximately half of the fruits had an orange tone.

Trickle ferti-irrigation tubes were located between each two rows of plants. Weekly irrigation management changed between one to three waterings depending on evapotranspiration, which is a function of the weather parameters, crop characteristics and environmental conditions (Allen *et al*., 1998). An analysis of the data obtained from the tensiometers and direct observation of the drainage equipment showed that no water stress occurred.

The fertilization programme was based on soil analysis. At the beginning of 1998 experiments, a NPK fertilizer was incorporated before planting and in 2000 this was not necessary. Ferti-irrigation was used to supply the necessary nutrients to the plants during the crop cycle according to the quantities presented in Table 2.2 (Abreu, 2004). Also a micronutrients solution was applied once a week and a calcium solution was applied during the harvesting period.

Table 2.2 – Quantities of nutrients applied by ferti-irrigation (kg $ha^{-1}$)

| | **N** | **$P_2O_5$** | **$K_2O$** | **Mg** |
|---|---|---|---|---|
| **Plantation to beginning of flowering** | 57 | 150 | 56 | 0 |
| **Flowering to beginning of harvesting** | 158 | 67 | 198 | 23 |
| **During harvesting** | 70 | 53 | 246 | 37 |
| **TOTAL** | 285 | 270 | 500 | 60 |

During the 1998 and 2000 experiments, the fungicides used were essentially preventive against powdery mildew and grey mould after visible symptoms were seen. Insecticides against white fly, leaf miner and tomato fruitworms were used when necessary. All treatments were the same in both greenhouses and are given in Table 2.3.

The 2000 crop required more treatments than in 1998, because the climatic conditions were more favourable for the development of pests and diseases, as it will be shown in this thesis.

Table 2.3 – Pesticides used during the experiments

| YEAR | DATE | ACTIVE SUBSTANCE | OBJECTIVE |
|---|---|---|---|
| **1998** | 14 March<br>28 May | Mancozeb | Powdery mildew |
| | 30 March<br>15 April<br>4 May | Cymoxanil<br>+<br>Propyneb | Powdery mildew |
| | 4 May<br>28 May<br>26 June | Deltamethrin | Leaf miner<br>White fly |
| | 28 May | Iprodione | Grey mould |
| **2000** | 4 February | Chlorpyrifos | Soil insects |
| | 22 March<br>14 April<br>10 May | Mancozeb | Powdery mildew |
| | 3 April<br>28 April<br>26 May | Cymoxanil<br>+<br>Propyneb | Powdery mildew |
| | 30 March | Endossulfan | Tomato fruitworms |
| | 21 June<br>29 June | Permetrine | Tomato fruitworms |
| | 5 May | Benomil | Grey mould |
| | 12 May<br>26 May | Iprodione | Grey mould |

### 2.1.3 Measuring and recording equipment

Climatic data were measured with three meteorological stations, two located in the centre of each greenhouse and the one outside. Air dry and wet bulb temperatures were measured every 10 minutes using a ventilated psychrometer fitted with PT100 sensors (Thies Clima, Goettingen, Germany) located at a height of 1.5 m. Global and photosynthetically active (PAR) radiations were measured at 10 second intervals using a Schenk 80101 starpyranometer (P. Schenk, Wien, Austria) and a special PAR sensor SKP210 (Skye Instruments Ltd., Powys, UK), respectively. Radiation sensors were located at heights of 2.8 m inside the greenhouse and 4.3 m outside, the former were above the crop. Wind speed was recorded every 10 seconds by an anemometer located

at a height of 4.5 m (Thies Clima, Goettingen, Germany). During the 1998 experiments, soil temperatures were measured at depths of 5, 20 and 50 cm in the PV greenhouse and at a depth of 20 cm outside and inside the CV greenhouse. In the case of the 2000 experiments, the soil temperatures were measured at surface level and at depths of 1, 5, 11, 20 and 50 cm in the PV greenhouse and at a depth of 20 cm outside and inside the CV greenhouse. In all the cases soil temperatures were recorded every 10 minutes using thermistors (Delta T-Devices, Cambridge, UK). Leaf temperature was measured every minute using infrared temperature thermometers (Everest Interscience Inc, Tucson, USA). The cover temperature was measured every minute using a thermocouple 0.2 mm in diameter, attached directly to the inner film surface.

Soil moisture content was measured every 10 minutes using electronic tensiometers (UMS GmbH, Munich); two were located inside the lysimeter and two outside the PV greenhouse. The water draining from the lysimeter was discharged through a buried pipe to a Rain-o-Matic rain gauge (Pronamic, Denmark) placed outside the greenhouse and protected from the external climate; this was measured every 10 minutes.

Data about water flow and duration of irrigation were recorded to compute the quantity of water supplied to the lysimeter, which was the same amount supplied to the rest of the greenhouse on a unit area basis.

All data were averaged and recorded on an hourly basis using two data logger systems from Delta - T Devices. Table 2.4 gives the measuring range and accuracy of the sensors used and Figure 2.4 shows several photos of the measuring and recording equipment.

Table 2.4 – Measuring range and accuracy of the sensors used in the experimental work

| SENSORS | MEASURING RANGE | ACCURACY |
|---|---|---|
| PT100 | 0 to 60 ºC | ± 0.15 ºC |
| Pyranometer | 300 to 3000 nm | ± 1 % (between 83 and 1334 W $m^{-2}$) |
| PAR | 400 to 700 nm | ± 5 % |
| Anemometer | 0.5 to 35 m $s^{-1}$ | ± 5 % |
| Thermistors | -20 to 80 ºC | ± 0.2 ºC (between 0 and 70 ºC) |
| Infrared thermometer | -40 to 100 ºC | ± 0.5 ºC |
| Tensiometers | 0 to 850 hPa | ± 5 % |
| Rain gauge | 0 to 99 999 impulses | ± 2 % |
| LI-3050A | 0 to 999 999.99 $cm^2$ | < 1 % |


Figure 2.4 – Measuring and recording equipment used in the experiments: a) outside pyranometer, PAR radiation sensor and anemometer, b) inside pyranometer and PAR radiation sensor, c) cover thermocouples, d) inside psychrometer, e) outside psychrometer, f) infra red thermometer, g) tensiometers, h) lysimeter, i) plugged lysimeter, j) rain gauge, k) drip rate checking, l) soil sampling, m) data loggers, n) psychrometers checking

Prior to installation, the sensors were tested in order to ensure they were working correctly and to check their accuracy of measurement.

The psychrometers were placed in the same room for several hours, assuming homogeneity of the air conditions (Figure 2.4n). Air dry and wet bulb temperatures were recorded and the maximum difference between the sensors of air dry temperature was 0.3ºC. Comparison between the instantaneous air temperatures measured using a mercury thermometer and the PT100 sensors showed negligible differences.

The pyranometers and PAR sensors were tested to verify the homogeneity between measurements. The procedure followed was the same for both sensors. They were located side by side and data recorded over several hours on sunny days. The pyranometers presented a maximum difference of 2% and the PAR sensors 5.5%. The anemometer was new and had been calibrated by the manufacturer.

The thermistors and the thermocouples were placed in an insulated box with water for several hours and showed a maximum difference of 0.2ºC and 0.4ºC respectively. These readings were compared with the reading of a mercury thermometer and were coincident. Infra-red thermometers were tested by directing the sensors at the same surface for several hours and the maximum difference was 0.4ºC.

Soil water tension is a direct measure of the availability of water in the soil for plants. Electronic pressure transducer tensiometers are used to measure soil water tension in the non saturated zone, water tension is measured and converted into a continuous electrical signal. In this work, each of the electronic tensiometers was tested following the manufacturer's instructions to obtain a proper relationship between soil water tension and the signal recorded by the logger (Figure 2.5).

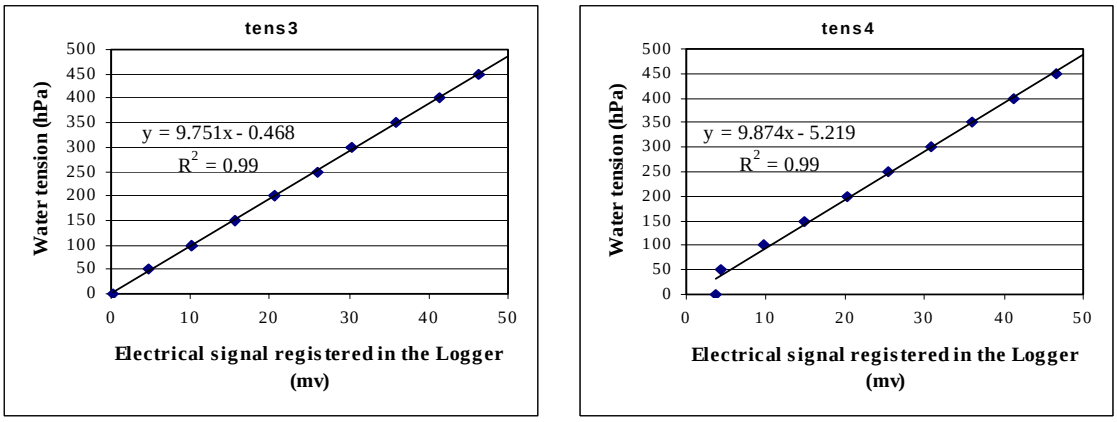



Figure 2.5 - Relation between the water tension in the soil and the electric signal registered by the logger obtained during the calibration process for two tensiometers

Additionally, samples of soil were collected, from several places inside the greenhouse, to analyse physical properties (% clay, lime, sand and organic matter) and to obtain the characteristic soil moisture content curve, which relates the volumetric water content with soil water tension (Figure 2.6). These analyses were carried out in the Soil Physics Laboratory of Évora University.

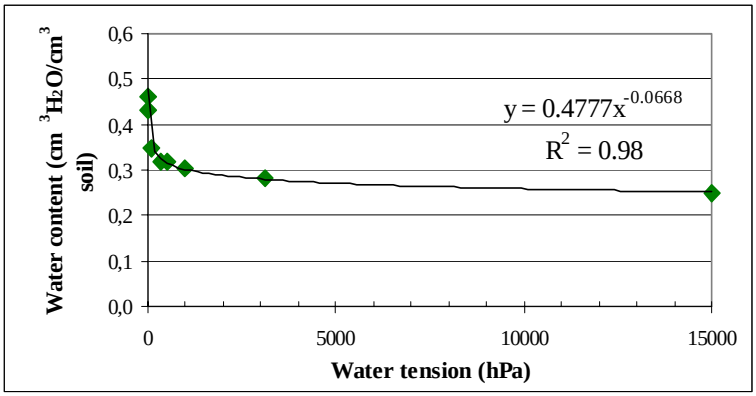



Figure 2.6 - Characteristic soil moisture content curve obtained by regression analysis

The drip rate of the irrigation system was checked several times during the experimental work at different places inside the greenhouse. The maximum amount measured over periods of 30 seconds was 30 ml of water and the minimum 24 ml. The mean drip rate was 27.3 ± 0.4 ml per 30 seconds. The rain gauge was adjusted so each spoon registered 4 ml of water. It was checked by comparison of the impulses recorded by the logger and the water collected in the rain collector; the error was less than 2 %.

Data on the evolution of the crop, such as plant growth, leaf area, flower production, fruit production, fruit weight and yield were also recorded. In 1998, samples of 10 leaves were collected to measure the leaf surface and the dry weight, several times during the crop cycle. The leaf area index was then estimated by using a relation based on the leaf surface and the dry weight (Abreu, 2004). During 2000 several plants were chosen at random and harvested between 12 April and 18 July to measure leaf area by destructive methods (three in each collect). These measurements were made in the Soil Physics Laboratory of Évora University using a LI-COR Model LI-3050A Transparent Belt Conveyer Accessory (Lambda Instruments, Nebraska, USA).

The cover material transmissivity and emissivity were measured in laboratory at Silsoe Research Institute.

## 2.2 The experimental design

### 2.2.1 Ventilation management

Management of natural ventilation was the main climate control technique used in these experiments. Two different natural ventilation treatments were randomly assigned to the greenhouses, one treatment to each greenhouse. One treatment was nocturnal or permanent ventilation (PV) during the day and night, while the other was classical ventilation (CV), in which the vents were open during the day and closed during the night. Details of the two natural ventilation treatments applied in both years of the experiments are given in Table 2.5.

Ventilation management was achieved by manually controlling the side wall window opening by rolling the film around a steel pipe. Roof openings were opened or closed by manual activation using an electrical motor that operated the roof window via a rack and pinion drive. Figure 2.7 presents some views of the different apertures of the side and roof windows utilised during the experimental work.

The environmental conditions in the two greenhouses were compared in order to evaluate the influence of the ventilation management strategy. The data was analysed statistically using ANOVA and t-tests, which enabled testing the significance of the treatments and determining if the treatment had a significant effect or not. The critical value (P) was usually set as 0.05 and if the significance level was lower than P, the treatment was considered to be significant.

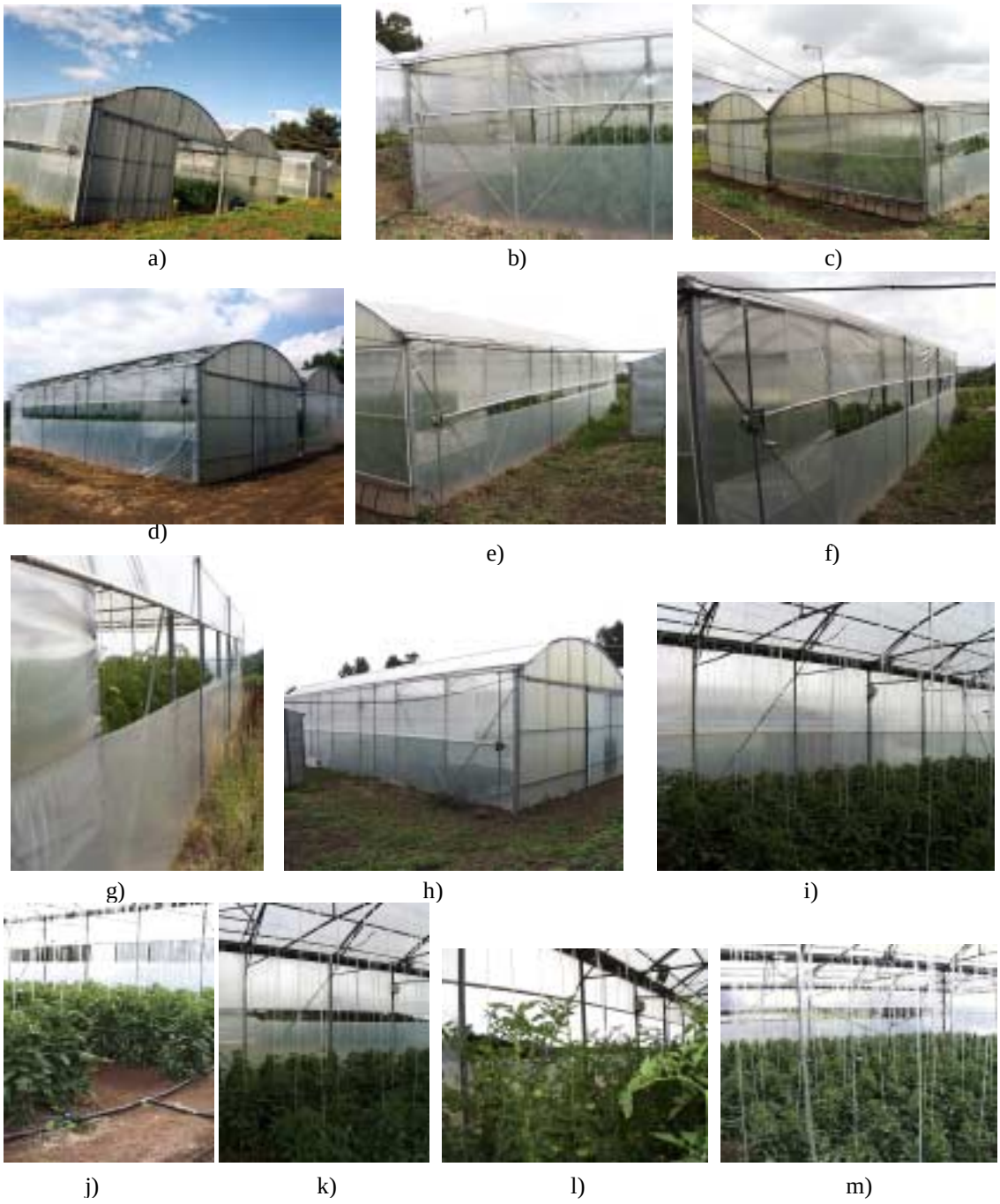



Figure 2.7 – Different views of the ventilation apertures of permanent and classical ventilated greenhouses: a) general view of the greenhouses, b) side opening 54 cm, c) cables connecting inside sensors and data loggers, d) side and roof openings, e) side opening 22 cm, f) detail of the rolling system, g) side opening 75 cm, h) external view of the night closed greenhouse, i) internal view of the night close greenhouse, j) internal view with side opening 54 cm, k) internal view with side opening 22 cm, l) internal view with side opening 75 cm, m) internal view with plant tutors

Table 2.5 – Schemes of ventilation management during the two years of experiments

| Year | Date | Ventilation period | Hour of opening | Hour of closure or reduction | PV greenhouse | | | | CV greenhouse | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Day | | Night | | Day | | Night | |
| | | | | | Height (cm) | Area ($m^2$) | Height (cm) | Area ($m^2$) | Height (cm) | Area ($m^2$) | Height (cm) | Area ($m^2$) |
| **1998** | 26/2 to 10/3 | A | 10:00 | 18:00 | 30 | 6 | 20 | 4 | 30 | 6 | 0 | 0 |
| | 11/3 to 3/5 | B | 9:00 | 18:00 | 41 | 8.2 | 10 | 2 | 41 | 8.2 | 0 | 0 |
| | 4/5 to 1/6 | C | 9:00 | 18:00 | 52 | 10.4 | 20 | 4 | 52 | 10.4 | 0 | 0 |
| | 2/6 to 17/6 | D | 9:00 | 19:00 | 52 | 10.4 | 20 | 4 | 52 | 10.4 | 20 | 4 |
| | 18/6 to 30/6 | E | 9:00 | 19:00 | 52S+25R | 17.4 | 20S +25R | 11 | 52S +25R | 17.4 | 20S+25R | 11 |
| | 1/7 to end | F | --- | --- | 52S+25R | 17.4 | 52S +25R | 17.4 | 52S +25R | 17.4 | 52S +25R | 17.4 |
| **2000** | 23/2 to 29/2 | --- | --- | --- | 22 | 4.4 | 22 | 4.4 | 22 | 4.4 | 22 | 4.4 |
| | 1/3 to 16/5 | G | 9:00 | 17:00 | 54 | 10.8 | 22 | 4.4 | 54 | 10.8 | 0 | 0 |
| | 17/5 to 30/5 | H | 9:00 | 18:00 | 54 | 10.8 | 22 | 4.4 | 54 | 10.8 | 0 | 0 |
| | 31/5 to end | I | --- | --- | 75 | 15 | 75 | 15 | 75 | 15 | 75 | 15 |

S – Side openings R – Roof openings

### 2.2.2 *Botrytis cinerea* assessment

In each greenhouse, groups of 4 plants were selected at random (3 groups in 1998 and 4 in 2000), and assumed to be representative of all the plants in the greenhouse (Figure 2.8). These groups of plants were used for disease observations and also for the crop evolution parameters, mentioned in section 2.1.3.

a) b)

Figure 2.8 – Group of plants selected for disease and crop observation (a) and schematic representation of the groups relative position in the PV greenhouse during 2000 (b)

The observations of *Botrytis cinerea* were started when the plants had 10 leaves. The number of leaflets with lesions in the 3 (1998) or 4 (2000) groups of plants were counted and removed from the greenhouse in order to reduce the amount of inoculum and to avoid errors in future observations. This was undertaken approximately once a week, between 14 May and 22 June 1998 and 28 April and 19 June 2000. This information enabled the determination of the Disease Severity (DS), as the total number of diseased leaflets on plants in all experimental groups, and the Disease Incidence (*DI*) as the percentage of infected plants, calculated as

$$DI = \frac{IP}{TOP} \times 100 \qquad (2.1)$$

where *IP* represents the number of infected plants and *TOP* the total number of observed plants. There were infrequent occurrences of stem lesions, rotten fruits and

fruits with ghost spots; when these did appear they were recorded and removed from the greenhouse.

In order to analyse the effect of ventilation management on disease occurrence, in each year the Disease Severity and the Disease Incidence in each greenhouse was compared using the ANOVA procedure.

### 2.2.3 Statistical analysis methodology

In this section the general methodology used to compare the climate and *Botrytis* data is explained. Detailed descriptions will be given in the appropriate chapters.

Descriptive statistics were used to characterise the main variables properties, environmental and *Botrytis* assessment. Comparison of climate and *Botrytis* data recorded in the PV and CV greenhouses were by means of variance analysis. It is generally assumed that the application of variance analysis (parametric tests) requires the data to meet the following conditions: independence of data, homogeneity of variances and normality of data. Non independence is more problematic than heterogeneity of variances and both are much more problematic than non normality of data (Underwood, 1998).

Data normality was evaluated by the Shapiro-Wilk (1965) test and the homogeneity of variances by Levene's (1960) test. Several authors mention that the analysis of variance is quite robust to non normality, which means that outcomes and interpretation are not influenced by non normality of the data (Underwood, 1998). This is particularly the case where the number of samples is large ($n > 30$) and balanced (the same number of observations) (Pestana and Gageiro, 2005).

Box (1953) *cit in* Underwood (1998) showed that the effects of heterogeneity of variances are much worse if the sample size differs from one population to another. If data are balanced and samples are relatively large, analysis of variance is robust to departures from this assumption (Underwood, 1998; Maroco, 2003; Pestana and Gageiro, 2005).

The dependent variables were studied using a general linear model (GLM), according to the statistical model:

$$Y_{ijk} = \mu + V_i + D_j + VD_{ij} + \varepsilon_{ijk} \qquad (2.2)$$

where $Y_{ijk}$ is the observation $k$ of the $i$ level of factor $V$ and $j$ level of factor $D$, $\mu$ the global mean, $V_i$ the effect of factor $V$, $D_j$ the effect of factor $D$, $VD_{ij}$ the interaction effect and $\varepsilon_{ijk}$ the random error of observation.

In all analyses values for which the probability of occurrence was higher than 95% ($P < 0.05$) were considered as significant. When the interaction effect was found to be significant, the means were compared using the methodology named designed comparison, using the Syntax Editor of SPSS programme. This procedure allowed the interactive effect in the individual analysis of each factor to be eliminated.

All the statistical analyses were undertaken using the statistical package SPSS 14.0®.

### 2.2.4 Modelling methodology

The general modelling methodology used to develop the various models and sub-models will be outlined in this chapter. Detailed explanation of the methodology followed for each will be given in the appropriate chapter.

The model presented in the thesis results from the combination of the climate and *Botrytis* models and each is composed of various sub-models (ventilation, evapotranspiration, heat transfer coefficients, radiation, etc.). Some of these sub-models were obtained by analysing the data recorded during the year 2000, others are an adaptation of existing models and others are the direct application of other published models.

Models were obtained by regression analysis, using the statistical programme SPSS® version 14.0. Linear models were preferred to nonlinear whenever they gave a satisfactory fit to the data. Regression models are powerful tools for predicting one dependent variable from one or more independent variables. In order to construct a regression model it is necessary to know the information about dependent and independent variables. The relation between these variables is then modelled and then only information about the independent variables is required. The main goal in the regression procedure is to create a model where the predicted and observed values are as similar as possible, so parameters of the model are selected in order to minimise the sum of the square deviations (least squares criterion) (Stockburger, 1998).

When several models were obtained, the selected one was the parsimonious model, which means the simplest with great explanatory power. The criteria used to select the best model was based on the adjusted determination coefficient ($r_a^2$) and the root mean square error (*RMSE*),

$$RMSE = \sqrt{MSE} \tag{2.3}$$

$$MSE = \frac{\sum_{i=1}^{n} (y_i^{'} - y_i)^2}{n} \tag{2.4}$$

where *MSE* is the mean square error or the errors variance, calculated by Eqn 2.4, in which $y_i^{'}$ is the predicted value, $y_i$ the observed value and *n* the number of observations. The *RMSE*, also known as the standard error of the estimate, is a measure of the error in prediction. The larger its value, the less well the regression model fits the data, and the worse the prediction.

The $r_a^2$ is a modification of the determination coefficient ($r^2$) proposed by (Zar, 1999), calculated as

$$r_a^2 = 1 - \frac{MSE}{MST} \tag{2.5}$$

where *MST* represents the total variance. The quantity $r_a^2$, represents the proportion of the dependent variable that is explained by the independent variables in the adjusted model.

The best model was considered as the one that had the highest $r_a^2$ and the lowest *RMSE* (Maroco, 2003). Also because the objective was to obtain a model with practical application, it was important to select independent variables that were informative, accessible and which would be measured accurately.

Criteria to indicate the correct fit of a regression model are that the residuals (or errors) are normally distributed and are quasi-orthogonally distributed between the independent variables. These criteria were verified using the residual analysis procedure presented in SPSS.

The climate model presented in this thesis is an adaption of the dynamic climatic model developed by Navas (1996) for a Mediterranean greenhouse. This model was adjusted to Portuguese conditions by using data recorded during the 2000 experiments. Data from different periods were used to develop or adapt the sub-models and other datasets were used to validate them.

The *Botrytis* model was constructed using 60% of the disease data recorded during the year 2000, with air temperature and relative humidity as the independent variables. Different ranges of cumulative hours of temperature and relative humidity were calculated from the data recorded. Several relations were obtained by regression analysis, using the backward routine of SPSS, which allowed the identification of the significant variables, for each period. The final model was then validated with data recorded in 1998 and the remaining 40% of 2000, following the principle that a model should be validated with a different set of data than that used to develop it.

The statistical parameters used to decide about the goodness fit of the models were the mean error (*ME*), the *RMSE* and the $r_a^2$. The *ME* is determined as:

$$ME = \frac{\sum_{i=1}^{n} (y_i' - y_i)}{n} \tag{2.6}$$

In general, a high adjusted determination coefficient and low mean and root mean square errors signify that the regression model fits the data well and the predictions will be good. These criteria were complimented with a graphical comparison of the measured and simulated values.

# 3. Greenhouse climate

## 3.1 Introduction

In Mediterranean countries, like Portugal, most greenhouses are very simple constructions, covered with polyethylene films and without heating systems. Environmental control in such greenhouses is essentially achieved using various ventilation techniques to control temperature and humidity, which are in most cases far from ideal and strongly dependent of outside conditions.

In this type of greenhouse, during cold weather, low night temperature and high relative humidity are the main environmental limiting factors, while during hot weather, high temperature is the main problem which frequently impedes greenhouse crop cultivation. Low temperatures reduce plant growth and fruit yield and lead to serious problems of fruit-setting due to poor pollen quality (Abad and Monteiro, 1989). High temperatures (> 30-35ºC) will cause many different types of damage to plants, such as inhibition of growth, fruit abortion and even death, depending on water availability. Day and night temperatures influence plant vigour, leaf size and time for fruit development.

For tomatoes, Jensen and Rarobaugh (2006) suggested a day temperature between 21 and 26ºC and a night temperature around 16-18.5ºC. Papadopoulos (1991) mentioned that the average 24 h temperature is responsible for the growth rate of the crop, the higher the temperature the faster the growth. Maximum growth occurs at day and night temperatures of approximately 25ºC while maximum fruit production is achieved with a night temperature of 18ºC and a day temperature of 20ºC. The recommended temperature is a compromise between these aspects, varying between 17 and 26ºC. However, in bright weather, temperatures higher than 26ºC do not damage plants although damage can occur above 29ºC. Willits and Peet (1998) presented results of yield reductions when the night temperature was over 22ºC. The minimum soil temperature should be around 14ºC (Papadopoulos, 1991).

Most crops can withstand a wide range of relative humidity, from very low to very high values, as long as the variation is not drastic or frequent (Papadopoulos, 1991). Humidity directly affects plant transpiration, which affects calcium uptake, hormonal distribution, ion pumping and stomata opening and closing. Several forms of expressing humidity can be used, the most common in greenhouse climate control being relative humidity (RH, %) and vapour pressure deficit (VPD, kPa). RH is the ratio of

water vapour pressure in the air to the maximum water vapour pressure at the same air temperature, and VPD is the difference between the maximum vapour pressure and the actual vapour pressure at a given temperature. Water moves from the roots to the leaves due to VPD between leaves and surrounding air, the higher the VPD the stronger the transpiration driving forces (Spomer and Tibbitts, 1997). The main disadvantage of using RH is that it does not say anything about the amount of water in the air, unless the temperature is given. However, the International Committee for Controlled Environment Guidelines (ANSI/ASAE, 2002) suggest that relative humidity is acceptable for reporting humidity until portable instruments are available to measure and display VPD.

High RH (> 90%) may reduce growth and is often responsible for nutrient deficiency symptoms; due to the reduction of plant transpiration, not drawing sufficient water and nutrients to the roots, particularly calcium, which can result in physiological disorders (Bakker, 1984). The reproductive phase can also be affected by high humidity. Picken (1984) concluded that pollination decreases significantly when relative humidity was too high. Low RH (< 50%) may induce high stomatal resistance and plant water stress, depending on the available water.

Hand (1988) suggested that the main negative effects of high humidity on the yield and quality of greenhouse crops could be due to the favourable conditions for fungal disease development, which is in agreement with Bailey (1984). Holder and Cockshull (1990) showed especially for tomato crops that high humidity caused a leaf area reduction, which was associated with low calcium concentrations, causing yield losses.

Jensen and Rarobaugh (2006) reported that most plants can function adequately in RH between 55 and 95%, while Nederhoff (1998) mentioned that relative humidity of around 80-85% is ideal for plant growth. For tomatoes, Jensen and Rarobaugh (2006) suggested an ideal humidity between 65 and 75% during the night and 80 to 90% during the day.

Greenhouse microclimate parameters such as the above mentioned air temperature and relative humidity and also leaf temperature and leaf wetness duration, influence the growth and development of crops and also the spread of certain diseases caused by fungi such as *B. cinerea*. This means, that environmental control should be defined in a way that good crop responses are guaranteed and at the same time avoid the

conditions favourable to disease development. This is not an easy objective to reach, but it is possible!

Until now we mentioned the favourable microclimate conditions for tomato crop development. However, it is also important to define the favourable conditions for *B. cinerea* development. In this chapter the favourable conditions for this fungus are described briefly, since a detailed review is presented in Chapter 5.

Concerning the favourable temperature, *B. cinerea* seems to develop, depending on the biological stage, in a wide range of temperature, between 0 and 28 ºC. The most important aspect to considerer is that the optimum temperature is coincident with the optimum for tomato crop, which contributes to the complexity of the environmental control on greenhouse tomatoes.

In respect of humidity, it is an even more complex microclimate parameter, since it is strongly dependent on the temperature. It is still not easy to say at what humidity the greenhouse air should be maintained. Also, it is well known, there is great variability inside the greenhouse, and especially near the crop boundary, in the conditions that influence crop and pathogen behaviour. If we assume that values of RH between 70 and 85% do not affect crop growth and development, the question remains: what should be humidity to control *B. cinerea*?

It is accepted by the majority of researchers that *B. cinerea* infection and development is favoured by conditions of high humidity. The question is: what should be the set points to RH? As expected, we can found several different values in the literature. Nederhoff (1997a) and Langston (2001) suggested, as a safe measure, to work with maximum RH of 85%. Zhang *et al*. (1997) in unheated greenhouses used the simple criterion of RH > 90% as the threshold value above which free water can be available on plants surface. Korner and Challa (2003) limited RH to a maximum of 93% for a maximum of 48 successive hours.

In spite of the well known microclimate variability inside greenhouses (Boulard *et al*., 2002; Bartzanas *et al*., 2004; Boulard *et al*., 2004; Soni *et al*., 2005; Ould Khaoua *et al*., 2006), for simplicity most control actions are based on temperature and humidity measurements made at a representative height, either fixed, usually in the centre of the greenhouse (Navas, 1996; Teitel and Tanny, 1999; Wang and Boulard, 2000; Abreu, 2004) or near the crop boundary (Yang, 1995; Boulard and Wang, 2002; Roy and Boulard, 2005). The greenhouse is considered as a perfectly stirred tank, which means the assumption of uniform conditions of temperature, humidity and $CO_2$ content and

uses the "big leaf" approach to treat the plant canopy and describe the sensible and latent heat exchange with the inside air.

This chapter includes a brief literature review on the principles of natural ventilation. The results of the experiments carried out during 1998 and 2000 are presented and analysed in order to study the effect of nocturnal ventilation on the greenhouse climate parameters.

## 3.2 Natural ventilation

Ventilation is one of the most important tools to control environmental conditions in greenhouse production. The air exchange between the inside and outside of a greenhouse influences heat and mass balances modifying the environmental characteristics, such as temperature, humidity and carbon dioxide concentration which affect the yield and quality of almost all crops. Insufficient ventilation can cause too high temperatures, too high humidity or severe $CO_2$ depletion while excessive ventilation may waste energy by additional heating during winter or cooling in summer. It also, may lead too low humidity conditions causing high transpiration and water stress in plants (Dayan *et al*., 2004). It is necessary to know the ventilation characteristics of a greenhouse in order to provide good control of the inside environmental conditions, to obtain a high quantity and quality of the crop.

The engineering of environmental control in greenhouses is complex due to time delays in the system. Covering materials are usually very thin and transparent to allow solar radiation to enter, but this permits changes in external conditions, such as outside temperature and wind to rapidly affect internal conditions. Knowledge of the physical principles of natural ventilation in conjunction with computer technology are important tools for ventilation control. However, nowadays, the better understanding of the physical processes involved in natural ventilation is still not enough to avoid some uncertainty in air exchange prediction, due to difficulties in performing accurate measurements and the lack of models that can be applied to different greenhouses (Kittas *et al*. 1996; Bailey, 2000a; Critten and Bailey, 2002; Ould Khaoua *et al*., 2006). Also, the heterogeneity of the climate parameters inside greenhouses and in consequence near the crop is one of the major causes of non-uniform production and quality.

Prediction and measurement of air exchange rates have been traditionally done using energy and mass balances (Chalabi and Bailey, 1989; Boulard *et al*., 1993;

Fernandez and Bailey, 1992; Teitel and Tanny, 1999; Baptista *et al*., 2001b; Dayan *et al*., 2004; Coelho *et al*., 2006; Harmanto *et al*., 2006), empirical models obtained by direct measurements of pressure differences between inside and outside (Hoxey and Wells, 1977; Hoxey and Moran, 1991; Boulard *et al.*, 1996; Kittas *et al.*, 1996; Papadakis *et al.*, 1996; Boulard *et al.*, 1998), tracer gas techniques (Bot, 1983; Boulard and Draoui, 1995; Baptista *et al*., 1999; Abreu *et al*., 2005) or with models based on the ventilation physical principles (Pérez-Parra *et al*., 2004). Recently sophisticated techniques have been developed and used for visualisation and determination of air flows, such as the computational fluid dynamics (CFD 2D or 3D), the sonic, hot-wire and laser Doppler anemometry (Mistriotis *et al.,* 1997; Boulard *et al*., 1999; Wang *et al.,* 1999a; Boulard and Wang, 2002; Boulard *et al*., 2002; Mistriotis and Briassoulis, 2002; Bartzanas *et al*., 2004; Shilo *et al,* 2004; Shklyar and Arbel*,* 2004; Montero *et al*., 2005; Teitel *et al*., 2005; Fatnassi *et al*., 2006; Ould Khaoua *et al*., 2006), or by the use of wind and water tunnels (Oca *et al*., 1999; Montero *et al.*, 2001). Detailed reviews were published by Critten and Bailey (2002) and by Roy *et al*. (2002).

Airflow through an opening is due to a pressure difference between the inside and outside (Bot, 1983; de Jong, 1990; Boulard *et al.*, 1996). In natural ventilation two forces are responsible for the pressure difference: one is the wind, which results in a modification of the pressure field around the building or obstacle, causing positive or negative pressure differences and the other is the thermal buoyancy or the stack effect, due to the difference between inside and outside air temperature and the resultant density gradient. It is assumed that air exchange is the result of a mean airflow that is driven by steady pressure fields due to wind, a turbulent airflow driven by fluctuating wind pressure and a stack effect caused by buoyancy forces (Boulard *et al*., 1997).

The basic ventilation mechanisms can be described by Bernoulli's equation, assuming the air speed ($v$) is constant over the opening, and the pressure difference ($\Delta P$) is given by:

$$\Delta P = \frac{1}{2}\xi\rho v^2 \tag{3.1}$$

where $\xi$ is the pressure drop coefficient and $\rho$ is the air density. From Eqn 3.1 and defining the discharge coefficient of the opening as $C_d = \xi^{-0.5}$, the air speed can be estimate as:

$$v = C_d\sqrt{\frac{2}{\rho}\Delta P} \tag{3.2}$$

This equation can be used to model all ventilation phenomena (Roy *et al*., 2002). The mechanisms involved in natural ventilation are complex, involving different and independent physical principles that must be studied separately. Contributing to this complexity is the fact that the air flows are influenced by the location and type of the greenhouse, location and size of vent openings and climatic characteristics (wind speed, wind direction and temperature difference). Bartzanas *et al*. (2004) and Ould Khaoua *et al*. (2006) investigated the influence of vent arrangement on the airflow and temperature distribution by CFD methods. Both concluded that the highest ventilation rate is not always the best criteria to evaluate the performance of different ventilation systems. The air speed within the crop, the aerodynamic resistance as well as the efficiency of ventilation on the flow and the air temperature difference between inside and outside must also be considered.

Ventilation removes sensible and latent heat from the greenhouse and the heat exchanges between the greenhouse air and outside are proportional to the ventilation flux. Models that can be used to predict ventilation rate will be presented in following sections.

### 3.2.1 Ventilation due to wind

The wind around a building creates a pressure field which induces pressure differences at the openings and hence causes airflow through them. The pressure differences may be positive or negative. Positive pressures force the air into the greenhouse, while suction, forces the air out of the greenhouse. The wind effect is usually split into two components (Bot, 1983; Boulard and Baille, 1995; Boulard *et al,* 1996): a steady effect, induced by a static pressure distribution related to the mean wind speed and a turbulent effect, induced by the fluctuating pressure distribution, linked with the turbulent characteristics of the wind interacting with the greenhouse or with the surroundings.

The wind static effect explains air movement in greenhouses with openings located in zones with different pressure coefficients, which is the case for most greenhouses constructed in Mediterranean regions, equipped with side and roof openings. However, Bot (1983) and de Jong (1990) suggested that in the case of greenhouses built in Northern Europe, with a high level of insulation, ventilator openings located in the roof and usually opened only on the leeward side, with the same pressure coefficient, the static effect does

not explain the air flux. In this case the explanation is the turbulent effect of the wind, induced by the instantaneous fluctuation of the wind.

The pressure fields created by these phenomena have been characterised by mean and turbulent pressure coefficients. However, due to difficulties in determining the relative contribution of each, most authors assume a global wind pressure coefficient, $C_w$, which is the result of both effects (Boulard and Baille, 1995; Kittas *et al.*, 1996; Baptista *et al.*, 1999; Bailey, 2000b; Fatnassi *et al.*, 2002). Applying Bernoulli's equation to air flow due to the wind pressure field, where $v_w$ is the wind speed measured at the reference height above the ground, the global pressure difference ($\Delta P_w$) is defined by:

$$\Delta P_w = \frac{1}{2}\rho C_w v_w^2 \tag{3.3}$$

Substituting $\Delta P$ in Eqn 3.2 by Eqn 3.3 and integrating the flux over half of the opening area, the air exchange rate ($V$) through the opening is given by Boulard and Baille (1995) and Kittas *et al.* (1996) as:

$$V = \frac{A}{2} C_d C_w^{0.5} v_w \tag{3.4}$$

where $A$ is the total area of the opening and, in the case of a single opening half of the area is the inlet and half is the outlet.

### 3.2.2 Ventilation due to thermal buoyancy

In places where the wind is strong, ventilation due to wind prevails. However, when no wind exists thermal buoyancy will create some air exchange. The size and location of the openings and the temperature difference between inside and outside determine the efficiency of natural convection.

During the day the air inside a greenhouse may be gaining heat directly from the heating system, and indirectly from solar radiation via the plants and the soil. If two openings exist at different heights, hot air from the inside exits through the higher opening while the same mass of cooler air enters through the lower opening. Air pressure varies with height and is different inside and outside the greenhouse. The air movement by natural convection through an opening is caused by this pressure difference (Bruce, 1973).

The pressure difference due to the stack effect results from the different vertical

pressure caused by the gradient of the air density between the inside and outside and can be expressed in Eqn 3.5 (Kittas *et al.*, 1996), where $H$ represents the vertical height of the opening, $g$ is the acceleration of gravity and $T_o$ is the outside temperature in Kelvin:

$$\Delta P_t = \rho g H \frac{\Delta t}{T_o} \tag{3.5}$$

Assuming the air behaves as a perfect gas and air temperature is homogeneous, Bernoulli's equation can be applied and substituting Eqn 3.5 into Eqn 3.2 the air speed through an opening can be calculated from:

$$v = C_d \left( \frac{2gH\Delta t}{T_o} \right)^{0.5} \tag{3.6}$$

Bruce (1978) published the theory of natural convection, defining the neutral plane where the density of air inside and outside is equal and no movement occurs at this level. In the lower half the outside pressure is higher than the inside. As a result the colder outside air enters through the lower half and the warmer inside air leaves through the upper half.

Boulard and Baille (1995) suggested a simple approximation for greenhouses with only roof or side openings, assuming that pressure and air speed are constant below and above the neutral plane. In this case the ventilation rate is given by Eqn 3.7:

$$V = \frac{A}{2} C_d \left( 2g \frac{\Delta t}{T_o} \frac{H}{4} \right)^{0.5} \tag{3.7}$$

In the case of two openings (both roof and side) the air exchange rate is deduced from a similar expression but including a factor $\varepsilon$, which represents the relative importance of roof ($A_R$) and side ($A_S$) areas on the total ventilation area ($A$). In this case $h$ is the vertical distance separating the centres of the roof and side vents.

$$V = \frac{A}{2} C_d \left( 2g\varepsilon^2 \frac{\Delta t}{T_o} \frac{h}{2} \right)^{0.5} \tag{3.8}$$

$$\varepsilon = \frac{2\sqrt{2b}}{(1+b)(1+b^2)^{0.5}} \qquad b = \frac{A_R}{A_S} \tag{3.9, 3.10}$$

### 3.2.3 Ventilation due to combined effects of wind and thermal buoyancy

With natural ventilation, usually both forces are present. Buoyancy can be neglected when the wind is strong. On the contrary with no wind, buoyancy is responsible for the air exchange. There is no consensus about the wind speed limit above which thermal buoyancy can be neglected. Some authors suggested 1.0 m $s^{-1}$ (Baptista *et al*., 1999; Roy *et al*., 2002), others 1.5 m $s^{-1}$ (Meneses and Raposo, 1987; Boulard and Baille, 1995; Kittas *et al*., 1996), others 2 m $s^{-1}$ (Boulard and Draoui, 1995; Papadakis *et al*., 1996) and others 3 m $s^{-1}$ (Bruce, 1986; Zhang *et al*., 1989). Bot (1983) reported that in a multi-span greenhouse the wind effect is dominant if $3v>\Delta t^{0.5}$ and Kittas *et al*. (1997) considered temperature driven ventilation is only significant if $v/\Delta t^{0.5}<1$.

Boulard and Baille (1995) studied several models used to predict ventilation rates and concluded that those which sum the pressure differences ($\Delta P = \Delta P_w + \Delta P_t$), and then determined the air flux gave a better agreement with measured values than those which sum the fluxes due to the individual effects. For greenhouses equipped with only roof or side vents, these authors showed that ventilation rate can be simulated with good accuracy by a model combining wind and buoyancy effects:

$$V = \frac{A}{2} C_d \left( 2g \frac{\Delta t}{T_o} \frac{H}{4} + C_w v_w^{\,2} \right)^{0.5} \tag{3.11}$$

The first term in parenthesis represents the thermal effect and the second one the wind effect. In the case of a greenhouse equipped with both roof and side vents, the ventilation rate is given by Boulard *et al*. (1997):

$$V = \frac{A}{2} C_d \left( 2g\varepsilon^2 \frac{\Delta t}{T_o} \frac{h}{2} + C_w v_w^{\,2} \right)^{0.5} \tag{3.12}$$

Ventilation coefficients, $C_d$ and $C_w$, are characteristic of the ventilation performance of each greenhouse type and have been identified by several authors. Compilation of these values for several types of greenhouses can be found in Boulard and Baille (1995), Bailey (2000b) and Roy *et al*. (2002).

Bailey (2000b) mentioned that $C_w$ seems to be independent of the greenhouse area, since values are very similar for a greenhouse either with 180 or 38,700 $m^2$ (between 0.071 and 0.14). The discharge coefficient, $C_d$, is a function of the ventilator characteristics and is generally between 0.6 and 0.8 with an average of 0.66 (Roy *et al*.,

2002). These values are usually determined without obstacles near the openings or the greenhouses and decrease when tall crops are present (Sase, 1989) or in the case of use of insect proof or shading nets (Fatnassi *et al*., 2002; Montero *et al.,* 1997; Pérez-Parra *et al.*, 2004). Several authors (Boulard and Baille, 1995; Kittas *et al.*, 1996; Baptista *et al*., 1999; Bailey, 2000b; Fatnassi *et al.*, 2002; Abreu *et al.*, 2005) have shown that the overall wind effect coefficient, $C_d C_w^{0.5}$, could be treated as a constant, varying between 0.20 and 0.27, depending on the range of wind speed.

## 3.3 Measured weather and greenhouse climates

External and internal climatic parameters were recorded during the experiments conducted in the greenhouses during 1998 and 2000. The results are now presented and analysed, and a comparison of the environmental conditions inside the two greenhouses made to understand the effect of the different ventilation management.

Values of external air temperature and relative humidity that were recorded are also presented and compared with the thirty year average (1961-1990) data of the Portuguese Meteorological Institute (IM) recorded at the local meteorological station (Tapada da Ajuda).

### 3.3.1 External conditions

#### 3.3.1.1 Air temperature and relative humidity

Figure 3.1 presents the mensal means of the outside air temperature and relative humidity (at 9:00 a.m.) obtained from measured hourly data during the two years of experimental work and the 30 years (1961-90) averaged climatological values (IM, 2006). The purpose is to compare the behaviour of these climatic parameters with those considered as the normal for this meteorological station.

Concerning the air temperature, it is clear that during March the temperature was higher in both years of experiments than the long term average values and the opposite occurred in April. After May, the behaviour was different for 1998 and 2000, with the first year being closer to the average data. In general the air temperature during 2000 was slightly higher than in 1998 and also higher than the average. During 1998 air

temperatures varied between higher and lower values than the average, but were always similar.

The Figure 3.1 also shows that the relative humidity was higher during 2000 than the thirty year average of the IM data and also than the 1998 values. In fact 2000 had an unusually rainy spring. This is a very important climatic characteristic which will contribute to the results of this research. A technical problem occurred between 2 May and 3 June 1998, with the measurement of the wet bulb temperature and this is the reason why there are no data on humidity for May 1998.

The external air temperature varied between 4 and 37 ºC in 1998 and between 4 and 39 ºC in 2000. The relative humidity variation was between 20% and 40% as the minimum absolute values for 1998 and 2000 respectively, with maxima of 100%.

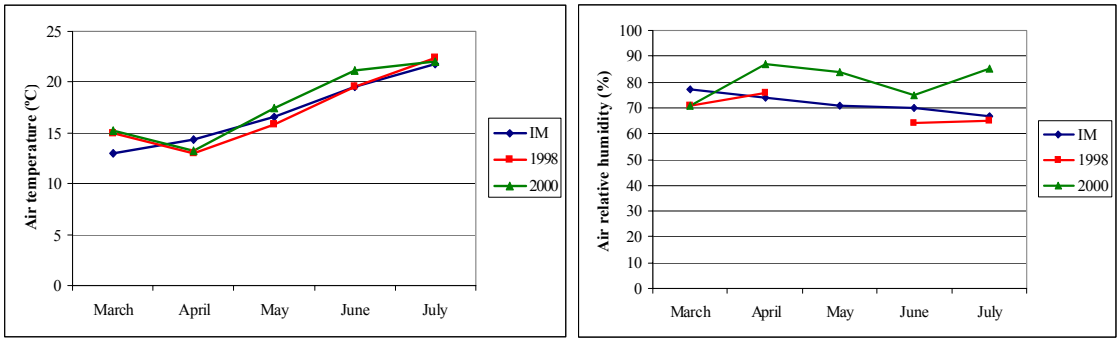



Figure 3.1 – Mensal means of the air temperature and relative humidity for 1998, 2000 and IM data (1961-90)

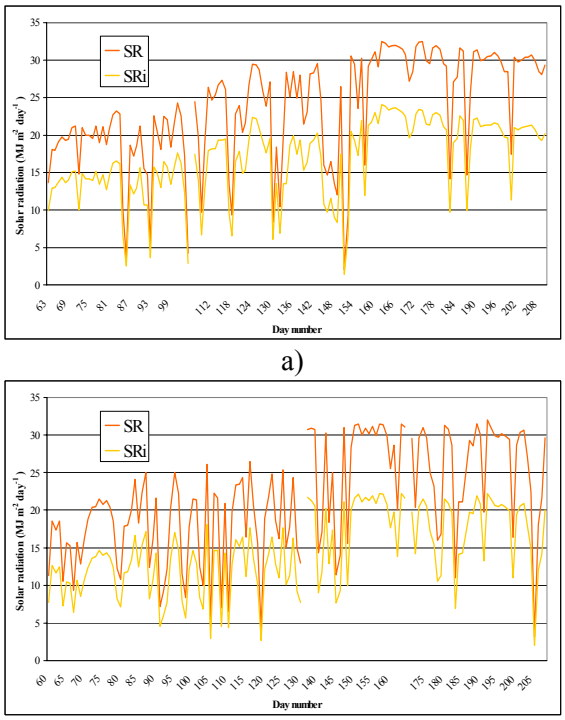
### 3.3.1.2 Global solar radiation

In Table 3.1 are presented the solar radiation characteristics measured during the two years of experimental work, expressed as the radiation flux (W $m^{-2}$) and the daily radiation integral (MJ $m^{-2}$ $d^{-1}$) for the outside (SR) and inside conditions ($SR_i$). Figure 3.2 shows the evolution of the solar radiation over the two years of experiments.

It is possible to observe that outside, the maximum radiation was very similar (±1070 W $m^{-2}$) for both years, being slightly higher during 1998. Inside the greenhouses the difference was more evident and this is explained by the cover optical properties degradation, due to the film age, which in 2000 was in the 3$^{rd}$ season. In fact, the cover transmissivity was 71% during 1998 and was reduced to 68% in 2000.

Table 3.1 – Solar radiation characteristics

| Year | | Radiation flux ($W\ m^{-2}$) | | Radiation integral ($MJ\ m^{-2}\ d^{-1}$) | |
|---|---|---|---|---|---|
| | | **SR** | **$SR_i$** | **SR** | **$SR_i$** |
| **1998** | Min. | 0 | 0 | 2.01 | 1.42 |
| | Max. | 1071.4 | 793.7 | 32.50 | 24.08 |
| | Mean | 273.7 | 194.4 | 23.63 | 16.76 |
| **2000** | Min. | 0 | 0 | 3.17 | 2.01 |
| | Max. | 1067.2 | 750.3 | 31.98 | 22.19 |
| | Mean | 251.2 | 170.0 | 21.51 | 14.57 |




a)

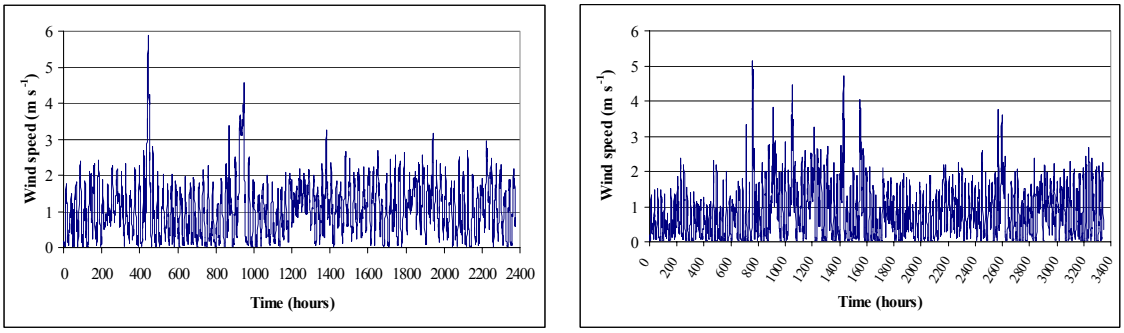
b)

Figure 3.2 – External (SR) and internal ($SR_i$) solar radiation measured during 1998 (a) and 2000 (b) experiments

### 3.3.1.3 Wind speed

Figure 3.3 shows the hourly variation of the wind speed recorded during the two years of experiments starting on 23 April 1998 and 1st March 2000 (some problems occurred with the anemometer at the beginning of the 1998 experiment). It is clear that wind speed is very variable and most of the time is below 2 m $s^{-1}$ in both years. Only 10% of the time in 1998 and 8% in 2000 was the wind speed higher than 2 m $s^{-1}$; the maximum values were 5.9 m $s^{-1}$ (1998) and 5.1 m $s^{-1}$ (2000). Also, wind speeds lower than 1 m $s^{-1}$ were very frequent (48% of the time in 1998 and 62% in 2000).

Since wind speed is an important factor influencing ventilation rate, and the main factor studied in this thesis is the nocturnal ventilation management, it is important to analyse separately the day and night periods. Table 3.2 presents the maximum and the mean values for the day, night and 24 h periods. It is shown that during the day wind speed was always higher than during the night. In fact, mean values during the night were approximately half than during the day.




a) b)

Figure 3.3 – Hourly values of wind speed for 1998 (a) and 2000 (b)

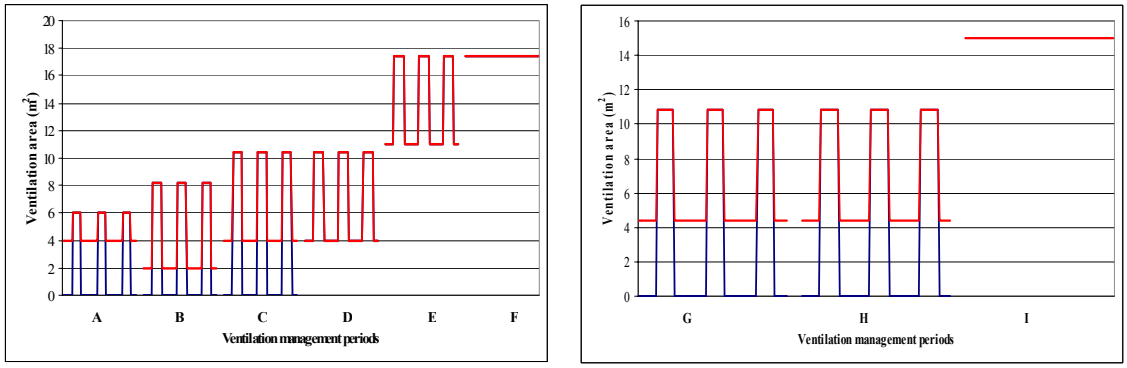
Table 3.2 – Maximum and mean wind speeds measured during 1998 and 2000

| Year | | Wind speed (m $s^{-1}$) | | |
|---|---|---|---|---|
| | | **Day** | **Night** | **24 h** |
| **1998** | Max. | 5.9 | 4.1 | 5.9 |
| | Mean | 1.6 | 0.7 | 1.1 |
| **2000** | Max. | 5.1 | 4.9 | 5.1 |
| | Mean | 1.2 | 0.6 | 0.9 |

### 3.3.2 Greenhouse climate parameters

The results presented begin on 4 of March 1998 and 1st March 2000 (day 63 and 60 of the year, respectively). Whenever justified on the basis of the main objectives of this thesis, the results were divided into periods with the same ventilation management, which means: 4 – 10 March (A), 11 March – 3 May (B), 4 May – 1 June (C), 2 – 17 June (D), 18 – 30 June (E), 1 July until the end (F) for the 1998 experiments and 1 March – 16 May (G), 17 – 30 May (H) and 31 May until the end (I) for the 2000 experiments.

The characteristic ventilation areas for the different ventilation periods, for day and night times, are shown in Figure 3.4, where CV is the greenhouse with classical ventilation and PV the one with nocturnal ventilation. During the day and for the ventilation periods D, E, F and I, both greenhouses had the same ventilation areas, which explains the red and blue lines superposition. Definition of day and night times was a function of the hour of opening/reducing or closing the ventilation apertures.




a) b)

Figure 3.4 – Ventilation areas for the several ventilation management periods for 1998 (a) and 2000 (b), —— PV greenhouse —— CV greenhouse

Internal air speed can be predicted as a function of the wind speed and the ventilator open areas (Wang *et al,* 1999a; Baptista *et al,* 2000b). During the night, if the vents are closed the air speed is dependent on the leakage and natural convection induced by buoyancy forces due to the temperature difference between greenhouse roof and soil surface, which is proportional to air temperature difference between inside and outside (Wang *et al*., 1999b).

#### 3.3.2.1 Air temperature

Details of the air temperature for the two years of experiments are shown in Table 3.3. As mentioned before, maximum temperatures were higher in 2000 than in 1998, but the minima and means were very similar for both years. The minimum temperatures are too low for growing a tomato crop, but since these were sporadic absolute values occurred during the days 103 (1998) and 95 (2000) with mean values of about 12 and 14 ºC respectively, it did not damage the crop. Considering all data in each of the years, no differences occurred between the two greenhouses, and the mean values were acceptable, since they were within the limits recommended for a tomato crop.

Table 3.3 – Air temperature (ºC) details for 1998 and 2000 experiments

| | **1998** | | | **2000** | | |
|---|---|---|---|---|---|---|
| | **Exterior** | **CV** | **PV** | **Exterior** | **CV** | **PV** |
| Max. | 36.7 | 38.3 | 39.8 | 38.9 | 41.1 | 41.3 |
| Min. | 4.4 | 4.1 | 4.9 | 4.1 | 4.8 | 4.9 |
| Mean | 17.2 | 18.5 | 18.9 | 17.6 | 19.3 | 19.4 |

Evolution of daily maximum, minimum and mean air temperature recorded inside the two greenhouses and outside, over the time of the experimental work is presented in Figure 3.5.

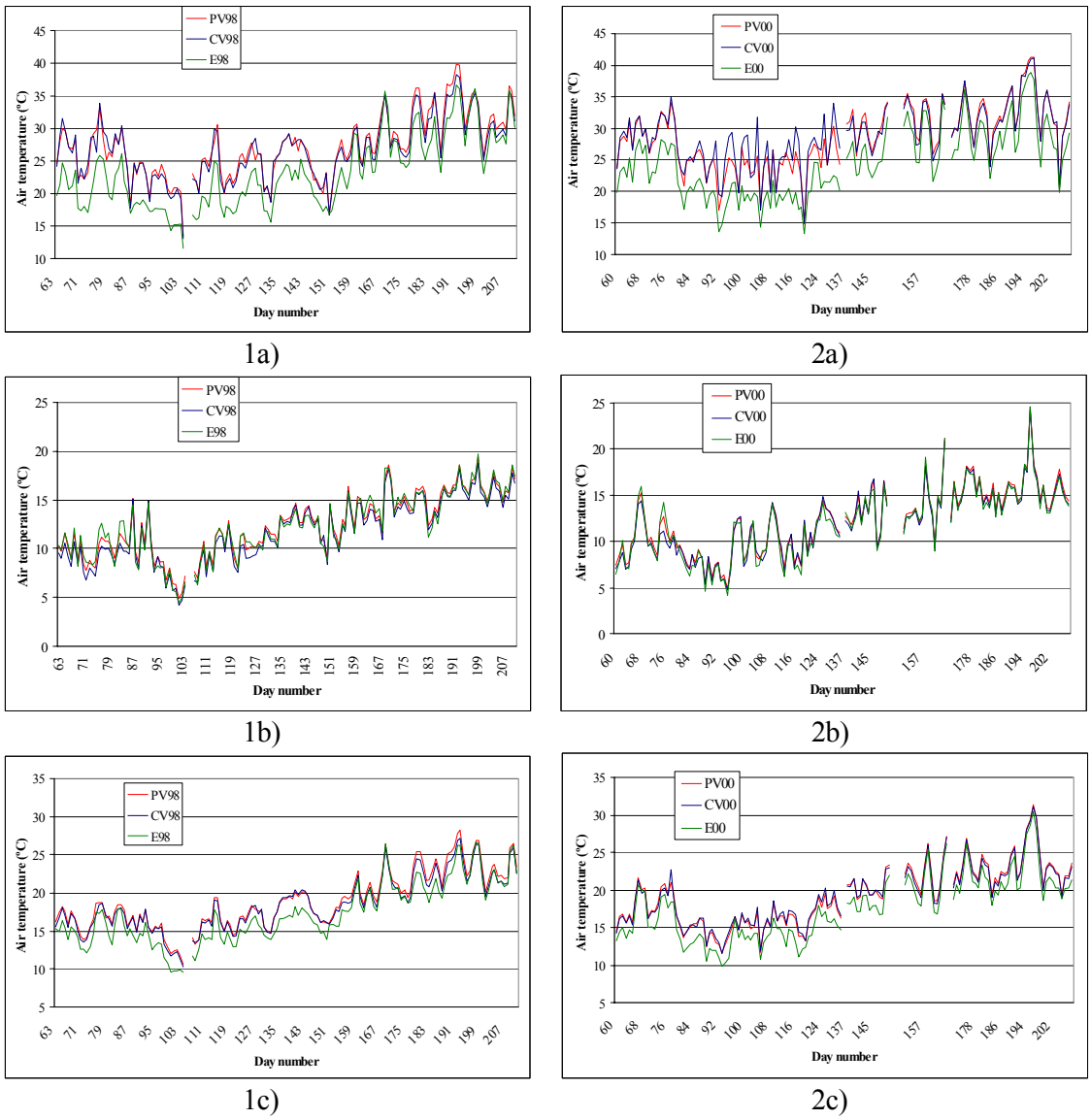


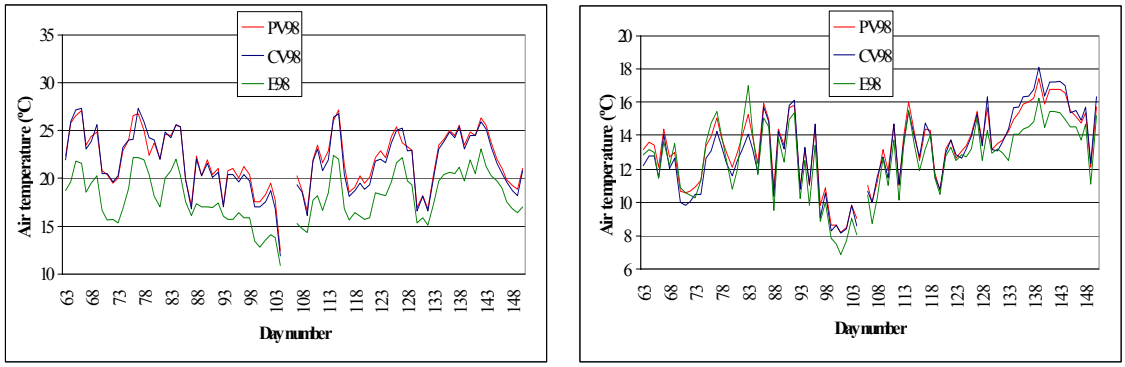

Figure 3.5 – Evolution of daily air temperature during 1998 (1) and 2000 (2) experiments. a) maximum, b) minimum and c) mean

A general analysis shows that the maximum air temperatures (1a and 2a), were always higher than 10ºC and directly related with the outside air temperature. These data correspond to day periods and in this case ventilation management was always the same in the PV and CV greenhouses. In fact, we can observe that the evolution in the two greenhouses was identical, except some days between days 86 and 128 in 2000, when the temperature in the CV greenhouse was higher than in the PV house. Since the

sensors were protected from the solar radiation we suppose this could be due to sporadic problems with the sensors that led to reading errors.

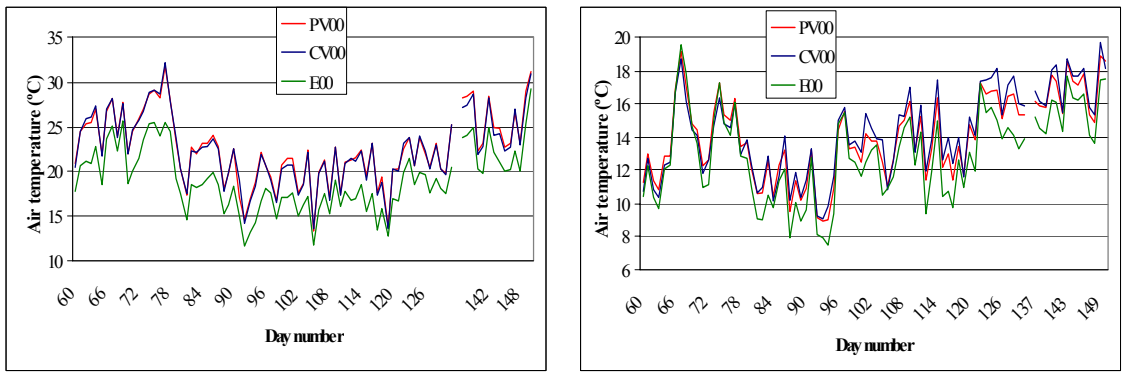
Minimum temperatures (1b and 2b) occurred during the night period, which correspond to the different ventilation management until the end of May for both years (day 150), when a minimum ventilation area was maintained in the PV greenhouse. The range of minimum temperatures was between 4 and 24 ºC, respectively in April and July. In fact, one could expect that the minimum temperature in the nocturnal ventilated greenhouse would be lower than in the closed one, since permanent ventilation reduces heat accumulation. However, in general, the temperature was very similar in both greenhouses, indicating that nocturnal ventilation did not cause additional problems by lowering the temperature, which could affect the crop. This can be exploited as an advantage of nocturnal ventilation. Thermal inversion phenomena occurred in both years, being more frequent in 1998 while during 2000 it was only sporadic. The temperature differences between inside and outside reached -3.2 and -3.1ºC (CV greenhouse) and -2.0 and -1.5ºC (PV greenhouse), respectively in 1998 and 2000. Nocturnal ventilation allowed diminishing this difference, which could be due to the convection heat transfer in the ventilated greenhouse that could balance the thermal radiation losses. Concerning the mean daily temperature (1c and 2c) it is again possible to observe that the temperatures in both greenhouses were very similar.

Since one of the main goals was to study the effect of permanent or nocturnal ventilation on the microclimate parameters, data relative to the period with different ventilation management was analysed in detail. Also, a complementary analysis (ANOVA) was undertaken in order to identify if, after the ventilation management became equal in both greenhouses, differences in temperature and humidity occurred. No significant differences were found for either climate parameter, $P = 0.264$ and 0.468, respectively. The evolution of the mean temperature during the day and the night for the period between 4 March and 30 May 1998 and 1 March and 30 May 2000 are shown in Figure 3.6 and 3.7 respectively.




a) b)

Figure 3.6 – Evolution of mean temperature during the day (a) and the night (b) for the period between 4 March and 30 May 1998




a) b)

Figure 3.7 – Evolution of mean temperature during the day (a) and the night (b) for the period between 1 March and 30 May 2000

Maximum differences between measured air temperatures in the CV and PV greenhouses for the day and night periods were -2.4 and -1.1ºC in 1998 and 2.0 and 1.3ºC in 2000. Looking to these values we can see an opposite behaviour for the two years analysed. In fact, we expected no large differences during the day period and some differences during the night due to the different ventilation management. Differences occurred during the day could be the result of sporadic door opening in one greenhouse and not in the other, to proceed with the necessary cultural practices or could be due to a reading error. During the night the difference of -1.1ºC corresponded to a night with temperature inversion in both greenhouses, when the air temperature in the ventilated greenhouse was higher than in the closed one. These results are in agreement with others presented by Meneses *et al.* (1994) and Boulard *et al.* (2004).

In spite of these particularities, a general analysis shows that no big differences occurred in air temperature of the two greenhouses for day and night periods, in each of the years studied, indicating that nocturnal ventilation did not significantly reduce air

temperature, which is in agreement with previous work by Meneses *et al.* (1994), Baptista *et al*. (2001a) and Boulard *et al.* (2004).

In order to confirm (or not) the last statement a statistical analysis was performed. As mentioned, one of the main goals was to study the effect of ventilation management, characterised by nocturnal ventilation in the PV greenhouse until the end of May (1998 and 2000). The data were divided in day and night periods, function of the hour of opening and reducing/closing the vents. Moreover, the ventilation management was changed during the experiments, so ventilation periods were also analysed in order to identify the possible influence on the results.

The statistical methodology was explained in detail in Chapter 2. The dependent variables were studied in conformity of the general linear model (Eqn 2.2), where the two fixed factors were the nocturnal ventilation management ($V$) and the ventilation period ($P$), according to the statistical model:

$$Y_{ijk} = \mu + V_i + P_j + VP_{ij} + \varepsilon_{ijk} \tag{3.13}$$

where $Y_{ijk}$ is the observation $k$ of the $i$ level of factor $V$ and $j$ level of factor $P$, $\mu$ the global mean, $V_i$ the effect of factor $V$, $P_j$ the effect of factor $P$, $VP_{ij}$ the interaction effect and $\varepsilon_{ijk}$ the random error of observation.

Statistical analysis confirmed that in both years, nocturnal ventilation did not cause significant differences in air temperature in the CV and PV greenhouses (Table 3.4). The other independent variable studied, the ventilation period, significantly influenced the air temperature (Table 3.5) while the interaction of both factors was not significant at the 95 % confidence level.

Table 3.4 – Mean air temperature (ºC) for day, night and 24 h periods ($\bar{x} \pm se$) from the beginning of March until the end of May for the CV and PV greenhouses

| | | Day | Night | 24 h |
|---|---|---|---|---|
| **1998** | CV | 21.7±0.3 | 13.2±0.3 | 16.3±0.2 |
| | PV | 21.9±0.3 | 13.3±0.2 | 16.5±0.2 |
| **2000** | CV | 22.5±0.4 | 14.3±0.3 | 17.1±0.3 |
| | PV | 22.6±0.4 | 14.1±0.3 | 17.0±0.3 |

Significant differences $P < 0.05$, $\bar{x}$ - mean, $se$ - standard error

Since in 1998 the ventilation periods were more than two, post-hoc tests were performed in order to identify any differences between the different periods. Appropriate tests were used, which in the cases of different n and non homogeneous

variances was the Games-Howell test and for different n and homogeneous variances was the Hochberg GT2 test (Pestana and Gageiro, 2005).

Table 3.5 – Mean air temperature (ºC) for day, night and 24 h periods ( $\bar{x} \pm se$ ), for each ventilation period from the beginning of March until the end of May

| | Vent Period | Day | | | Night | | | 24 h | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | CV | PV | CV + PV | CV | PV | CV + PV | CV | PV | CV + PV |
| **1998** | A | 25.0±0.8 | 24.9±0.6 | 25.0±0.5$^{a}$ | 12.6±0.3 | 13.2±0.3 | 12.9±0.2$^{a}$ | 16.7±0.4 | 17.1±0.3 | 16.9±0.2$^{a}$ |
| | B | 20.9±0.4 | 21.2±0.4 | 21.1±0.3$^{b}$ | 12.1±0.3 | 12.4±0.3 | 12.3±0.2$^{a}$ | 15.5±0.2 | 15.8±0.3 | 15.6±0.2$^{b}$ |
| | C | 22.2±0.5 | 22.5±0.5 | 22.4±0.4$^{c}$ | 15.3±0.3 | 15.1±0.3 | 15.2±0.2$^{b}$ | 17.8±0.3 | 17.8±0.3 | 17.8±0.2$^{a}$ |
| **2000** | G | 21.9±0.5 | 21.9±0.4 | 21.9±0.3$^{A}$ | 13.7±0.3 | 13.5±0.3 | 13.6±0.2$^{A}$ | 16.4±0.3 | 16.3±0.3 | 16.4±0.2$^{A}$ |
| | H | 25.6±0.7 | 26.0±0.7 | 25.8±0.5$^{B}$ | 17.3±0.4 | 16.7±0.4 | 17.1±0.3$^{B}$ | 20.4±0.4 | 20.4±0.4 | 20.4±0.3$^{B}$ |

Different letters mean significant differences P < 0.05, $\bar{x}$ - mean, $se$ - standard error

Table 3.5 shows that, in both years, and for each of the ventilation periods, temperatures inside CV and PV greenhouses were always similar for the day, night and 24 h periods. Again, this is particularly important during the night, showing that nocturnal ventilation do not decrease significantly the air temperature.

In both years the temperature differences found, for the studied ventilation periods, showed a direct influence of the weather conditions, which varied along the experiments. For example, in 1998, over 24 h the outside air temperature was similar for the periods A and C (15.2 and 16.0ºC) while it was lower for the period B (13.9ºC), and these conditions influenced the results presented in Table 3.5.

#### 3.3.2.2 Relative humidity (RH)

Air humidity is a challenging parameter to monitor, but it is critical to plant-water relations and infection by foliar pathogens. Relative humidity can be used as an indication of the risk of condensation and thus can be useful to control fungal diseases (Nederhoff, 1997b).

Relative humidity (RH) was calculated using an algorithm presented by Allen *et al*. (1994), which allowed determination of the saturated vapour pressure (e*) as a function of the air dry bulb temperature, and the actual vapour pressure *(*e) as a function of the measured air dry and wet bulb temperatures. By definition RH =100 e / e* and is expressed in %.

Some technical problems occurred with the measuring equipment of the wet bulb temperature located outside the greenhouses between 2 May and 3 June 1998 and after 19 June 2000, and inside the classical ventilated greenhouse after 30 May 1998,

which is why some data are missing. Table 3.6 shows maximum, minimum and mean values of the relative humidity recorded outside and inside the greenhouses during the two years of experimental work.

Table 3.6 –Relative humidity (%) details for 1998 and 2000 experiments

| RH | 1998 | | | 2000 | | |
|---|---|---|---|---|---|---|
| | **Exterior** | **CV** | **PV** | **Exterior** | **CV** | **PV** |
| Max. | 100 | 100 | 100 | 100 | 100 | 100 |
| Min. | 19.4 | 25.6 | 24.6 | 41.8 | 52.7 | 53.4 |
| Mean | 70.1 | 81.9 | 71.4 | 80.4 | 83.8 | 82.6 |

Most authors assume an RH lower than 50% as too low and very high above 90%. Concerning the minimum values of RH it can be seen that during 1998 conditions of too low humidity occurred in both greenhouses, while during 2000 extreme conditions of minimum RH never happened. Saturation conditions occurred in both years. The mean RH was within the values refereed by several authors as the ideal for plant growth (Nederhoff, 1998; Jensen and Rarobaugh, 2006).

Figure 3.8 presents the evolution of daily maximum, minimum and mean air relative humidity, inside the two greenhouses and outside. A general observation from all figures is that the inside RH is very dependent on the outside RH and in general it reached higher values during 2000 than during 1998.

The RH inside the greenhouses was lower or higher than outside depending on the latent heat balance. However, the absolute humidity (g $m^{-3}$), was always higher inside the greenhouses due to the presence of the crops, which is in agreement with Nederhoff (1997c), and in fact explains why it is possible to reduce humidity inside a cropped greenhouse by ventilation even in a rainy day (depending on the temperature)!

The maximum RH (1a and 2a) occurred during the night corresponding to the different ventilation management until the end of May (day 150). It is possible to observe, for both years, that RH in the closed greenhouse was always higher than in the ventilated house. These results are in accordance with those presented by Morgan (1984), Meneses and Monteiro (1990), Abreu *et al*. (1994), Baptista *et al*. (2001a) and Boulard *et al*. (2004), and shows that nocturnal ventilation is an appropriate tool to reduce humidity inside unheated greenhouses. The range of the maximum RH was between 60-70% and saturation, respectively in 1998 and 2000 and it is possible to see a much higher difference of RH between the two greenhouses during 1998 than 2000. Analysing Figure 2a) it is possible to see some approximation between the values of RH

of the CV and PV greenhouses after day 150, when ventilation management became permanent in both greenhouses and so the components of the latent heat balance were similar.

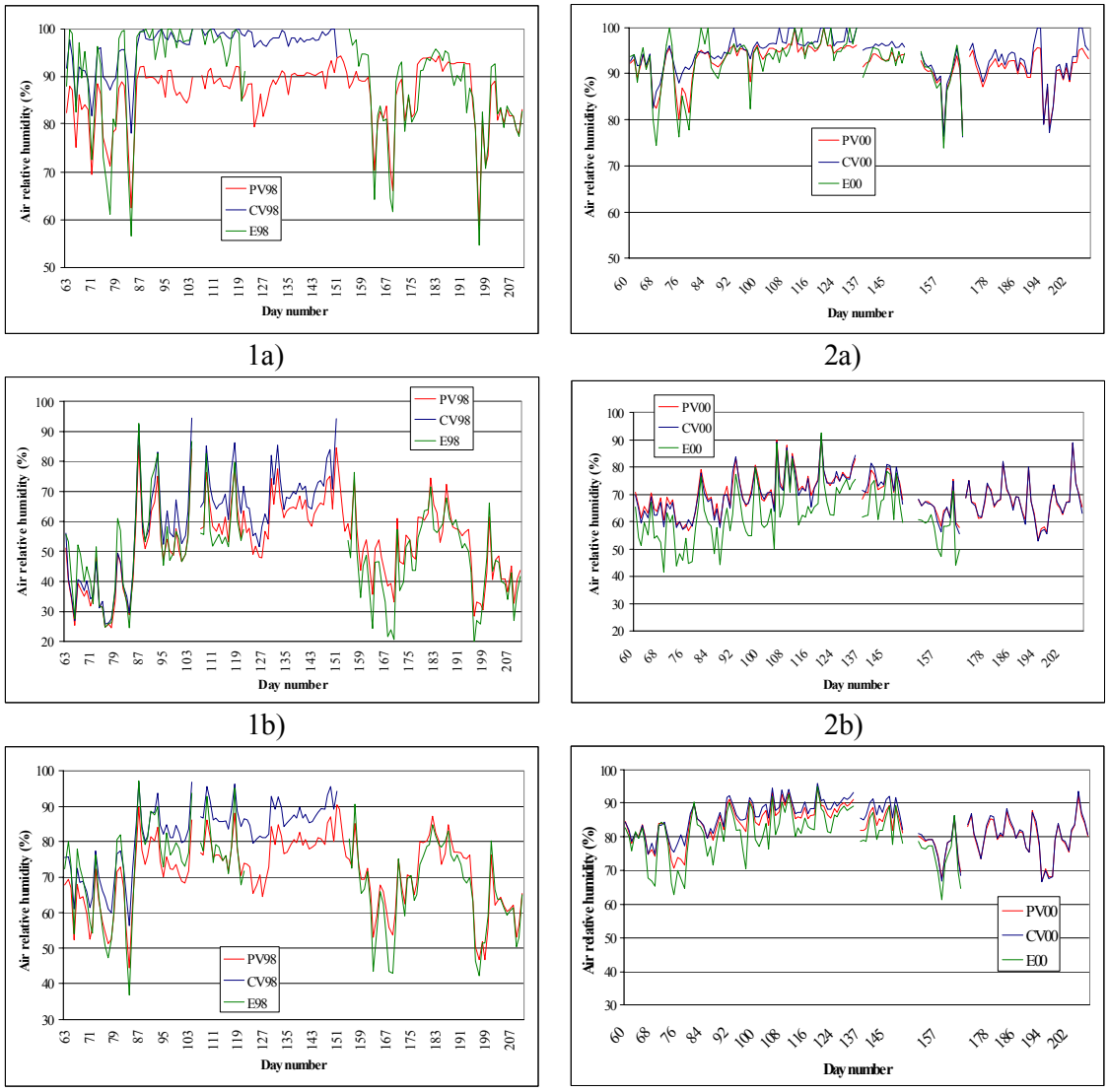



Figure 3.8 – Evolution of daily air relative humidity during 1998 (1) and 2000 (2) experiments. a) maximum, b) minimum and c) mean

The minimum values of RH (1b and 2b) occurred during the day, when ventilation management was similar in both greenhouses and it was expected that no big differences would occur, since the components of the energy balances were similar. In fact, this happened in 2000 (Figure 2b), when the RH was very similar in both greenhouses. However, this did not occur during 1998 (Figure 1b), as after day 95 there was a significant difference between the RH measured in the two greenhouses. As mentioned before some errors were detected in measuring the wet bulb temperature

inside the classical ventilated greenhouse by the end of May. In fact this difference may suggest that errors could have started before, since no big differences were found for the air temperature in this period, which could explain this behaviour.

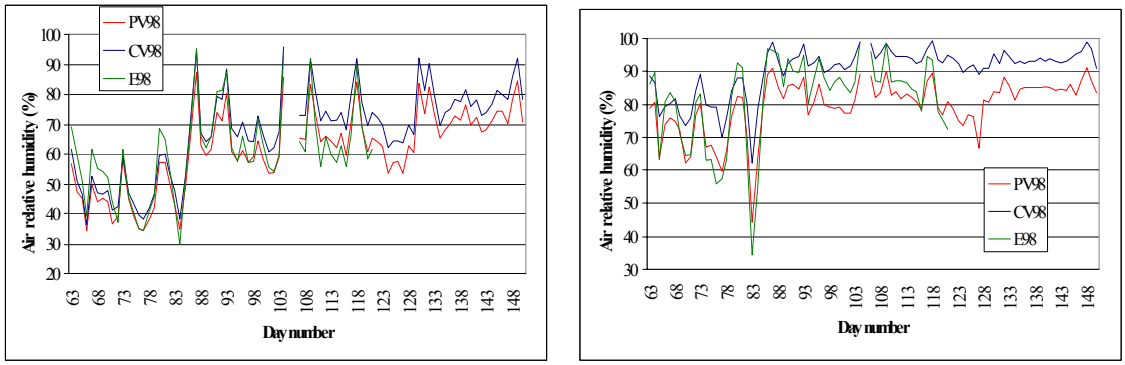
Concerning the mean daily relative humidity (1c and 2c), it is possible to observe that the RH in PV was in general lower than in the CV greenhouse, varying between 40 and 95% in 1998 and between 60 and 95% in 2000. These ranges of relative humidity are very frequent in unheated greenhouses and have been reported by several authors (Meneses *et al*., 1994; Zhang *et al*., 1997; Boulard *et al*., 2004). Again the straight connection between outside and inside RH is evident and it can also be seen that at the beginning of the experiments, when the crop was small and the transpiration rate was lower, it was more frequent to find days with the outside RH higher than inside, especially during 1998. A general look shows that for most of the time the RH was between 60 and 90% during 1998 and between 70 and 90% in 2000, which are acceptable values for a tomato crop but the maximum limit can be a risk as far as *B. cinerea* disease is concerned.

Table 3.7 shows the maximum and mean differences ($RH_{CV}$ - $RH_{PV}$) between the RH recorded in the two greenhouses for the period corresponding to the ventilation management characterised by nocturnal ventilation in the PV greenhouse while in the CV vents were closed in the late afternoon. Figures 3.9 and 3.10 present the evolution of the mean relative humidity during the day and the night over the same period.

Table 3.7 – Maximum and mean differences between relative humidity measured in the CV and PV greenhouses (percentage points)

| **Difference $RH_{CV}$ - $RH_{PV}$** | **1998** | | **2000** | |
|---|---|---|---|---|
| | Day | Night | Day | Night |
| Maximum | 10.0 | 22.5 | 3.4 | 9.8 |
| Mean | 6.0 | 10.5 | 0.1 | 2.6 |

Analyses of Table 3.7 shows the differences for day and night periods were higher in 1998 than in 2000. In fact, during 1998 nocturnal ventilation allowed a maximum difference of 22.5 while in 2000 it was reduced to 9.8. In 1998 a mean reduction of 10.5 was achieved but only 2.6 in 2000, which could be the result of the already mentioned different outside conditions. During the 2000 day period, differences were small while in 1998 they were much higher. It has been mentioned before, that, in 1998, measurement error could be the main explanatory reason.



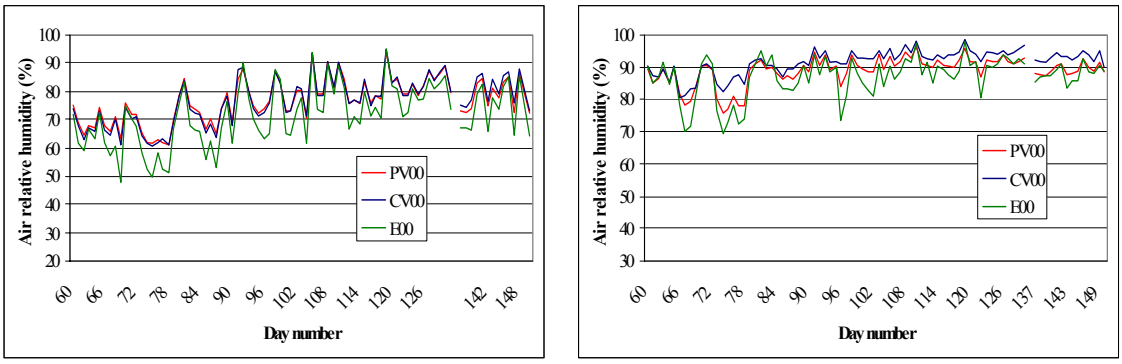

a) b)

Figure 3.9 – Evolution of mean relative humidity during the day (a) and the night (b) for the period between 4 March and 30 May 1998

Figure 3.9a) shows the mean RH for the day period, with equal ventilation in both greenhouses. The mean relative humidity inside the CV greenhouse changed within a range of 36 and 96%, while inside the PV greenhouse the variation was between 34 and 87%. Clearly shown again is the low inside relative humidity during the first phase of experiments, corresponding with small LAI and low plant transpiration rates (and also low outside RH). Figure 3.9b) shows the mean RH for the night period, with different ventilation management, closed and ventilated greenhouses. During the night the mean RH was between 62 and 99% in the CV greenhouse and between 44 and 91% in the PV house. If we look at the values only for the period after day 90, when a LAI of approximately 2.0 was reached, we can say that during the night period most of the time the RH inside the PV greenhouse was between 70 and 90%, while in the CV house it was almost always higher than 90%. This is in fact, one of the most important results, since it proves the capability of controlling the humidity by using nocturnal ventilation. This limit of 90% has been used by several authors as the maximum allowed for avoiding favourable conditions to condensation and the consequent *B. cinerea* attack. In Chapter 5 the severity and the incidence of grey mould disease caused by *B. cinerea* will be analysed and these aspects of the relative humidity will assume great importance!

The evolution of the mean relative humidity during the day and the night for 2000 is presented in Figure 3.10. During the day, the mean relative humidity was similar in both greenhouses, within a range of 60 and 95%, which is explained by the same ventilation management, as mentioned before. Figure 3.10b) shows the mean RH for the night, when ventilation management was different in the two greenhouses. During the night the mean RH was between 80 and 98% in the CV greenhouse and between 75 and 96% in the PV greenhouse. Again, as a first impression no big

differences occurred, mainly concerning the maximum values. In fact, the biggest difference is between the minimum values, showing that inside the closed greenhouse the RH was never below 80% while in the PV house it reached values around 75%. Using the same principle as before, looking only for the period after day 90, (LAI > 2.0), we can say that the RH inside the CV greenhouse was almost always higher than 90%, while in the PV some values lower than 90% were recorded, although not frequently.




a) b)

Figure 3.10 – Evolution of mean relative humidity during the day (a) and the night (b) for the period between 1 March and 30 May 2000

The following more systematic analysis was made to determine if nocturnal ventilation had a significant effect on the relative humidity conditions inside the greenhouses. The results obtained are shown in Table 3.8, and it is possible to confirm that nocturnal ventilation had a significant effect on the relative humidity, except during the day period of 2000. In fact, it was expected that during the day period of 1998, no differences occurred, since the ventilation was equal in both greenhouses. This aspect has already been mentioned and this analysis only confirms the comments made before. The significant differences found for the 24 h periods are mainly due to the fact that the night period was longer than the day period, which had a strong effect on the final results.

Table 3.8 – Mean air relative humidity (%) for day, night and 24 h periods ( $\bar{x} \pm se$ ), from the beginning of March until the end of May for the CV and PV greenhouses

| | | Day | Night | 24 h |
|---|---|---|---|---|
| **1998** | CV | $67.7 \pm 1.6^{a}$ | $90.2 \pm 0.8^{a}$ | $81.9 \pm 1.0^{a}$ |
| | PV | $61.5 \pm 1.4^{b}$ | $79.7 \pm 0.9^{b}$ | $73.0 \pm 1.0^{b}$ |
| **2000** | CV | $76.6 \pm 0.9$ | $91.5 \pm 0.4^{A}$ | $86.4 \pm 0.5^{A}$ |
| | PV | $76.6 \pm 0.8$ | $88.9 \pm 0.5^{B}$ | $84.6 \pm 0.6^{B}$ |

Different letters mean significant differences $P < 0.05$, $\bar{x}$ - mean, $se$ - standard error

Table 3.9 shows the results of the analysis conducted to understand the effect of the ventilation period, which was found to be significant for the 1998 experiments but non significant for the 2000 ones. This Table shows also that relative humidity inside the CV greenhouse was always higher than in the PV house, with higher differences during 1998, as mentioned before.

Table 3.9 – Mean air relative humidity (%) for day, night and 24 h periods ($\bar{x} \pm se$), for each ventilation period from the beginning of March until the end of May

| | Vent Period | Day | | | Night | | | 24 h | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | CV | PV | CV + PV | CV | PV | CV + PV | CV | PV | CV + PV |
| **1998** | A | 48.9±2.9 | 46.0±2.5 | 47.4±1.9$^{a}$ | 81.3±1.8 | 74.2±2.1 | 77.8±1.6$^{a}$ | 70.6±1.9 | 64.8±2.2 | 67.7±1.6$^{a}$ |
| | B | 65.6±2.1 | 59.3±1.9 | 62.5±1.4$^{b}$ | 89.8±1.1 | 78.6±1.2 | 84.2±1.0$^{b}$ | 80.5±1.4 | 71.2±1.4 | 75.9±1.1$^{b}$ |
| | C | 76.4±1.6 | 69.7±1.6 | 73.1±1.2$^{c}$ | 93.2±0.4 | 83.1±1.0 | 88.1±0.9$^{c}$ | 87.2±0.8 | 78.4±1.2 | 82.8±0.9$^{c}$ |
| **2000** | G | 77.8±1.0 | 78.1±1.0 | 78.0±0.7 | 91.2±0.5 | 88.8±0.6 | 90.0±0.4 | 86.1±0.6 | 84.6±0.7 | 85.3±0.5 |
| | H | 80.4±1.3 | 78.6±1.3 | 79.5±0.9 | 92.8±0.4 | 89.2±0.5 | 90.9±0.5 | 88.0±0.8 | 85.1±0.8 | 86.5±0.6 |

Different letters mean significant differences P < 0.05, $\bar{x}$ - mean, $se$ - standard error

Some care should be taken when analysing data of relative humidity, without knowing the temperature. If we look at the data relating to 1998, we observe that the RH is increasing with time and this is understandable since the plants were growing, the LAI increasing and transpiration rate was increasing. In fact, the relative humidity inside the greenhouses is the result of a mass balance, strongly influenced by the outside conditions and by the crop's presence. So, the combination of these factors could result in an increase of RH with time, explaining the differences found between the several ventilation periods. However, we are talking about relative humidity, which can be used for our proposal, but a more detailed analysis should be undertaken considering an absolute measure of humidity. Nevertheless, it can be considered as a logical tendency. Considering the 2000 experiments, no significant differences were found which could be due to the very long G period when compared with the H (only 15 days in May).

Figures 3.11 (1998) and 3.12 (2000) show the number of hours per day with relative humidity higher than 90% inside the CV and PV greenhouses during the periods with different ventilation management. Again, these figures confirm the strong difference between the two years. During 1998 the difference between the two greenhouses was evident (total of 904 h in CV *versus* 104 h in PV) while in 2000 it was not so marked (total of 1052 h in CV *versus* 832 h in PV). However, nocturnal ventilation resulted in a decrease of relative humidity also during 2000, in spite of the very humid spring. This is an important effect, since it shows that even with more humid conditions; nocturnal ventilation can be used as an environmental control

technique which can help to reduce humidity inside unheated greenhouses. However, it must be accentuate that on very wet rainy days with similar inside and outside temperatures, permanent ventilation can result in an increase of the inside RH.

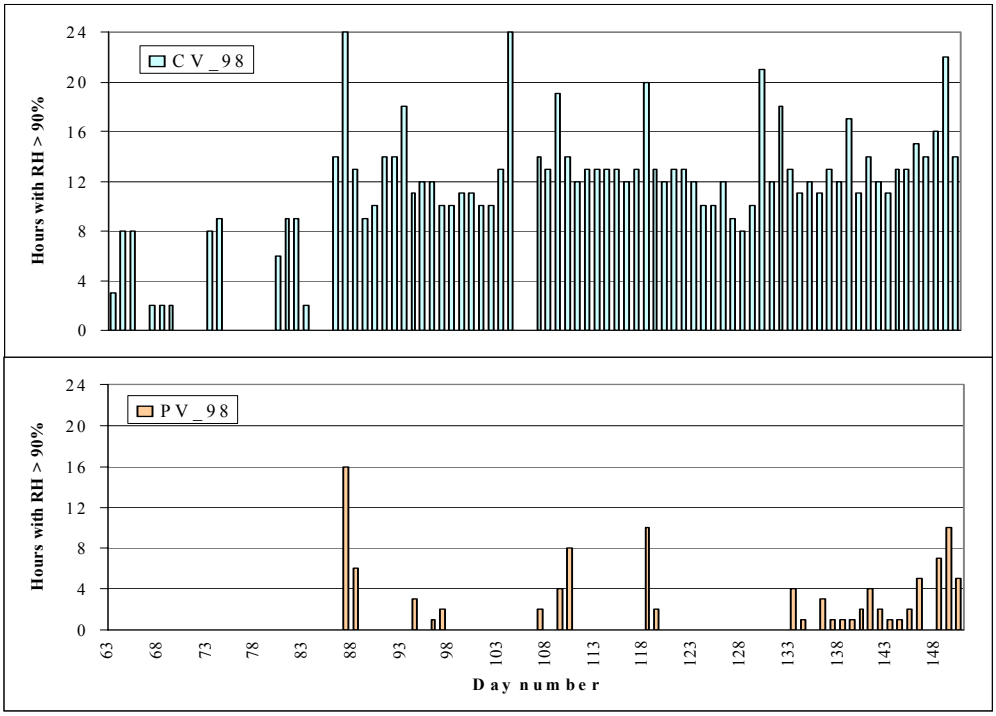



Figure 3.11 – Number of hours per day with relative humidity higher than 90% inside the CV and PV greenhouses between beginning of March and the end of May of 1998

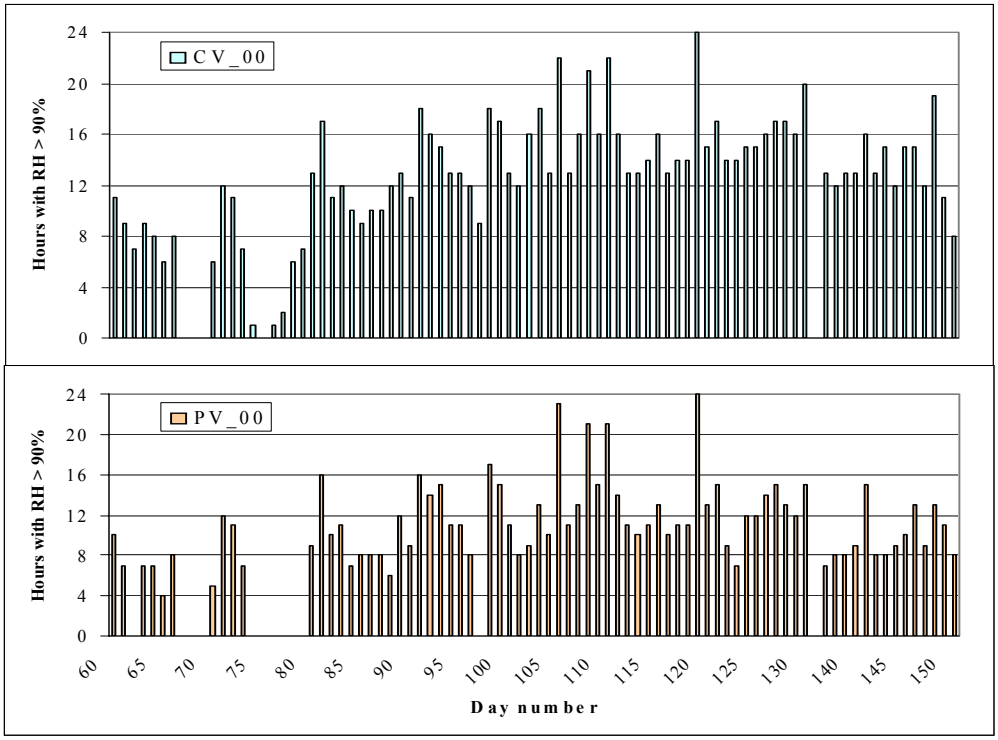



Figure 3.12 – Number of hours per day with relative humidity higher than 90% inside the CV and PV greenhouses between beginning of March and the end of May of 2000

The next Tables present the percentage of the experimental time when the RH was higher (3.10) or lower (3.11) than certain RH values, for the two experimental years.

Table 3.10 – Percentage of time when RH exceeded specific values during the experiments in 1998 and 2000

| RH | 1998 | | 2000 | |
|---|---|---|---|---|
| (%) | CV | PV | CV | PV |
| 95 | 26.4 | 3 | 14.5 | 4.8 |
| 90 | 44.2 | 8.9 | 39.8 | 31.4 |
| 85 | 55.4 | 25.5 | 54.3 | 49.2 |
| 80 | 63.4 | 37.6 | 64.9 | 61.7 |
| 75 | 70.2 | 48.1 | 75.0 | 74.5 |
| 70 | 78.2 | 56.6 | 86.1 | 86.6 |
| 65 | 84.4 | 67.1 | 93.8 | 94.5 |
| 60 | 89.2 | 75.6 | 98.3 | 98.5 |

Table 3.11 – Percentage of time when RH was lower than specific values during the experiments in 1998 and 2000

| RH | 1998 | | 2000 | |
|---|---|---|---|---|
| (%) | CV | PV | CV | PV |
| 60 | 10.8 | 24.4 | 1.7 | 1.5 |
| 50 | 6.4 | 11.2 | 0.1 | 0.1 |

Assuming a RH between 70 and 85% is near the ideal for tomato plant growth it seems that RH conditions were more favourable in 2000 than in 1998. In fact, during 2000 the relative humidity inside the CV greenhouse was within this range for 31.8% of the experimental time and for 37.4% in the PV greenhouse, while during 1998 it was 22.8% in the CV greenhouse and 31.1% in the PV house. Also, it is clear that the best conditions occurred inside the nocturnal ventilated greenhouse for both years, with biggest difference during 1998.

The other aspect related with relative humidity, which is very important to the objectives of this thesis, is the limit beyond which condensation is favoured and that should be considered to control *B. cinerea*. For this analysis, it was assumed that value is 90%, as suggested by Zhang *et al*. (1997). For both years, humidity conditions were more propitious for *B. cinerea* development inside the classical ventilated greenhouse than in the nocturnal ventilated house. Concerning the 1998 experiments, inside the CV greenhouse the RH was higher than 90% during more than 44% of the experimental time while in the PV house it was less than 10%. If we look to the 2000 experiments the difference is not so evident, but again the RH was higher than 90% for almost 40% of

the experimental time and in the PV house was only about 31%, which was enough to improve *B. cinerea* control, as it will be shown in Chapter 5.

Problems related with low humidity can also occur in greenhouses, causing damage to the crops. The percentage of the experimental time with low RH is presented in Table 3.11. Assuming that a RH lower than 60% is below optimal and below 50% is too low (Nederhoff, 1998), we can see that during 2000 no problems due to low RH occurred at all and during 1998 only inside the PV greenhouse was the RH lower than 60% for a little more than 20% of the time. This potential problem was minimised by supplying sufficient water through the irrigation system so the plants could meet the higher transpiration rate.

#### 3.3.2.3 Ventilation rate

The ventilation periods were defined in Section 2.2.1 as function of the opening areas, hour of opening, reducing or closing the vents and also the type of openings (side only or both side and roof). Table 3.12 presents the parameters used to calculate the air exchange rate for each of the studied periods. The coefficients $C_d$ and $C_w$ were selected from the literature for the same type of greenhouse (Boulard *et al.*, 1997).

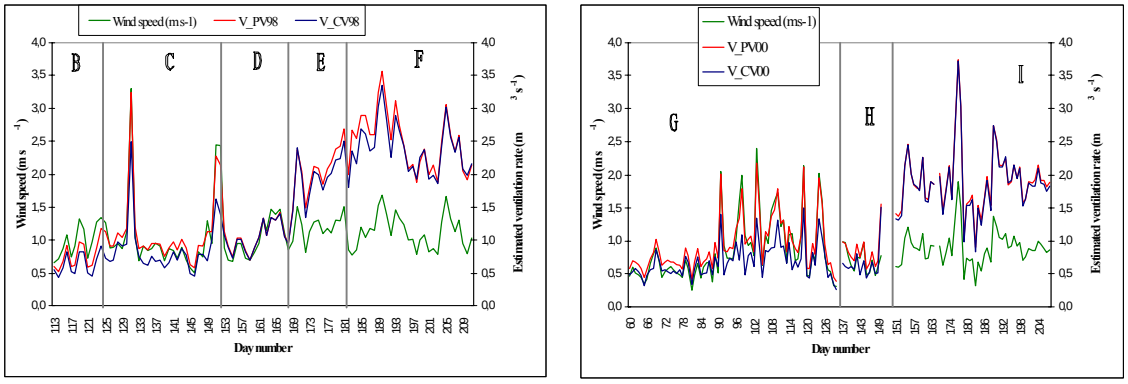
Table 3.12 – Parameters used to determine the ventilation rates

| Year | Date<br>Day number | Ventilation period | Height (m)<br>Area ($m^2$)<br>PV greenhouse | | CV greenhouse | | $C_d$ | $C_w$ | $\varepsilon_{day}$ | $\varepsilon_{night}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Day | Night | Day | Night | | | | |
| 1998 | 26/2 to 10/3 | A (S) | 0.30 | 0.20 | 0.30 | 0 | 0.67 | 0.15 | | |
| | 57 - 69 | | 6 | 4 | 6 | | | | | |
| | 11/3 to 3/5 | B (S) | 0.41 | 0.10 | 0.41 | 0 | 0.67 | 0.15 | | |
| | 70 - 123 | | 8.2 | 2 | 8.2 | | | | | |
| | 4/5 to 1/6 | C (S) | 0.52 | 0.20 | 0.52 | 0 | 0.67 | 0.15 | | |
| | 124 - 152 | | 10.4 | 4 | 10.4 | | | | | |
| | 2/6 to 17/6 | D (S) | 0.52 | 0.20 | 0.52 | 0.20 | 0.67 | 0.15 | | |
| | 153 - 168 | | 10.4 | 4 | 10.4 | 4 | | | | |
| | 18/6 to 30/6 | E (S + R) | 1.2 | 1.4 | 1.2 | 1.4 | 0.67 | 0.08 | 1.15 | 0.68 |
| | 169 - 181 | | 17.4 | 11 | 17.4 | 11 | | | | |
| | 1/7 to end | F (S + R) | 1.2 | 1.2 | 1.2 | 1.2 | 0.67 | 0.08 | 1.15 | 1.15 |
| | 182 - 211 | | 17.4 | 17.4 | 17.4 | 17.4 | | | | |
| 2000 | 1/3 to 16/5 | G (S) | 0.54 | 0.22 | 0.54 | 0 | 0.67 | 0.15 | | |
| | 60 - 136 | | 10.8 | 4.4 | 10.8 | | | | | |
| | 17/5 to 30/5 | H (S) | 0.54 | 0.22 | 0.54 | 0 | 0.67 | 0.15 | | |
| | 137 - 150 | | 10.8 | 4.4 | 10.8 | | | | | |
| | 31/5 to end | I (S) | 0.75 | 0.75 | 0.75 | 0.75 | 0.67 | 0.15 | | |
| | 151 - 208 | | 15 | 15 | 15 | 15 | | | | |

S – side openings, R – roof openings

Ventilation rate was estimated for both greenhouses and for both years, considering the combined effect of wind and thermal forces by using Eqn 3.11 (Boulard and Baille, 1995) when the greenhouses were ventilated only with side openings. When air exchange was achieved with both side and roof openings Eqn 3.12 (Boulard *et al.*, 1997) was used.

Figure 3.13 shows the mean daily wind speed and the estimated ventilation rate for the two years and for the different ventilation periods.




a) b)

Figure 3.13 – Wind speed and estimated ventilation rate for 1998 (a) and 2000 (b)

It is possible to see that the estimated ventilation rate follows the wind speed in both greenhouses in both years. Ventilation periods B, C, G and H are characterised by the nocturnal ventilation in the PV greenhouse and that can be identified in the figures, since mean ventilation fluxes were always higher in the PV greenhouse than in the CV house. Ventilation management was equal for both greenhouses after the beginning of June. For the periods D and I, with side openings only, the estimated ventilation rate were almost coincident in both greenhouses, which was expected since ventilation parameters were similar, the only difference being the temperature difference. Figure 3.13a) shows between days 175 and 193, corresponding to the periods E and F, with side and roof openings, the air exchange rate in the PV greenhouse was higher than in the CV house. As mentioned before, wind speed and openings areas were exactly the same in both greenhouses, so the only explanation is the different $\Delta t$, which presented a maximum difference between the two greenhouses of 1.2ºC, leading to a maximum ventilation rate difference of 0.37 $m^3$ $s^{-1}$. These are not statistically significant at the 95% confidence level and this temperature difference could be due to an error of the measuring equipment.

Ventilation periods E, F and I are characterised by an important increase of the opening areas, which correspond to an increase in the air exchange rates. It is well known that the ventilation rate is proportional to the wind speed and vent areas. Boulard *et al*. (1997) and Wang *et al*. (1999a) proved that vent opening and wind speed together explained more than 50% of the ventilation rate.

In Table 3.13 are shown the averages of wind speed, opening areas, estimated ventilation rate and temperature difference (Δt) between inside and outside, for the different ventilation management periods. It is apparent from the results that ventilation rate tends to increase from the beginning until the end, following the increase in vent areas. Since the mean wind speed had little variation (between 0.7 and 1.2 m $s^{-1}$), the vents area were the most important factor in determining the total ventilation flux.

Table 3.13 – Average ventilation characteristics of the ventilation periods

| | Vent. period | Wind speed (m $s^{-1}$) | Opening areas ($m^2$) | | Estimated ventilation rate ($m^3$ $s^{-1}$) | | Δt (ºC) | |
|---|---|---|---|---|---|---|---|---|
| | | | PV | CV | PV | CV | PV | CV |
| **1998** | B | 0.9 | 4.3 | 2.9 | 0.7 | 0.6 | 1.9 | 1.6 |
| | C | 1.1 | 6.4 | 3.9 | 1.1 | 0.9 | 1.7 | 1.8 |
| | D | 1.0 | 6.7 | 6.7 | 1.1 | 1.0 | 1.3 | 0.7 |
| | E | 1.2 | 13.7 | 13.7 | 2.1 | 2.0 | 1.4 | 0.7 |
| | F | 1.1 | 17.4 | 17.4 | 2.5 | 2.4 | 1.4 | 0.7 |
| **2000** | G | 0.9 | 6.6 | 3.6 | 0.9 | 0.7 | 1.8 | 2.0 |
| | H | 0.7 | 6.8 | 4.1 | 0.8 | 0.7 | 2.0 | 2.0 |
| | I | 0.9 | 15.0 | 15.0 | 1.8 | 1.8 | 1.4 | 1.0 |

One of the criteria to evaluate the ventilation efficiency is the temperature difference, as the more efficient air exchange gives lower values. In general the lower Δt values were attained when the ventilation flux was high. No significant differences were found between the two greenhouses during the 2000 experiments, while in 1998, Δt for periods D, E and F, in the CV greenhouse were half of those obtained in the PV house. Again, this could be due to errors already mentioned. Analysing only the evolution of Δt in the CV greenhouse, shows that the lowest value was reached either with only side openings or with both side and roof openings. Papadakis *et al*. (1996), Bartzanas *et al*. (2004) and Coelho *et al*. (2006) found an increase in ventilation efficiency by combining side and roof openings, not confirmed by our data. However, this could be due to the small range of the estimated air exchange rates, which did not enable the influence of ventilator configuration to be determined.

Figures 3.14 and 3.15 are relative to the experimental period with different ventilation management in the CV and PV greenhouses. The air temperature difference between the inside and outside as a function of the estimated ventilation rate is presented in Figure 3.14.

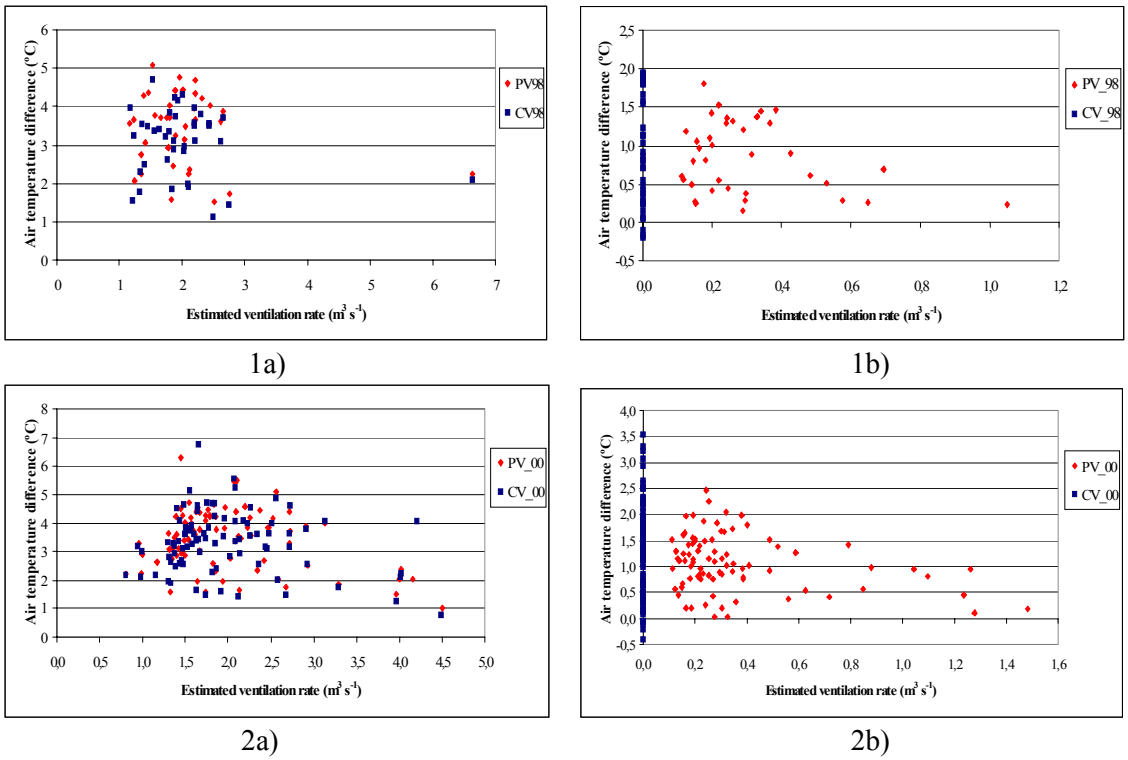



Figure 3.14 – Air temperature difference between the inside and outside *versus* the estimated ventilation rate for 1998 (1) and 2000 (2), for day (a) and night (b) periods

The first impression is that the estimated ventilation flux did not strongly influence the temperature difference, either during the day or the night periods, in either year. Since ventilation is only one of the components of the energy balance, it is evident that other factors contributed to define the air temperature.

In fact, during the day in both years, the temperature differences were randomly distributed over the ventilation rates. During the night, in general, the $\Delta t$ was in the same range in both greenhouses and was independent of the estimated ventilation flux, being slightly higher in the CV greenhouse during the 2000 experiments (max of 3.6ºC).

Figure 3.15 provides the air relative humidity as a function of the estimated ventilation rate.

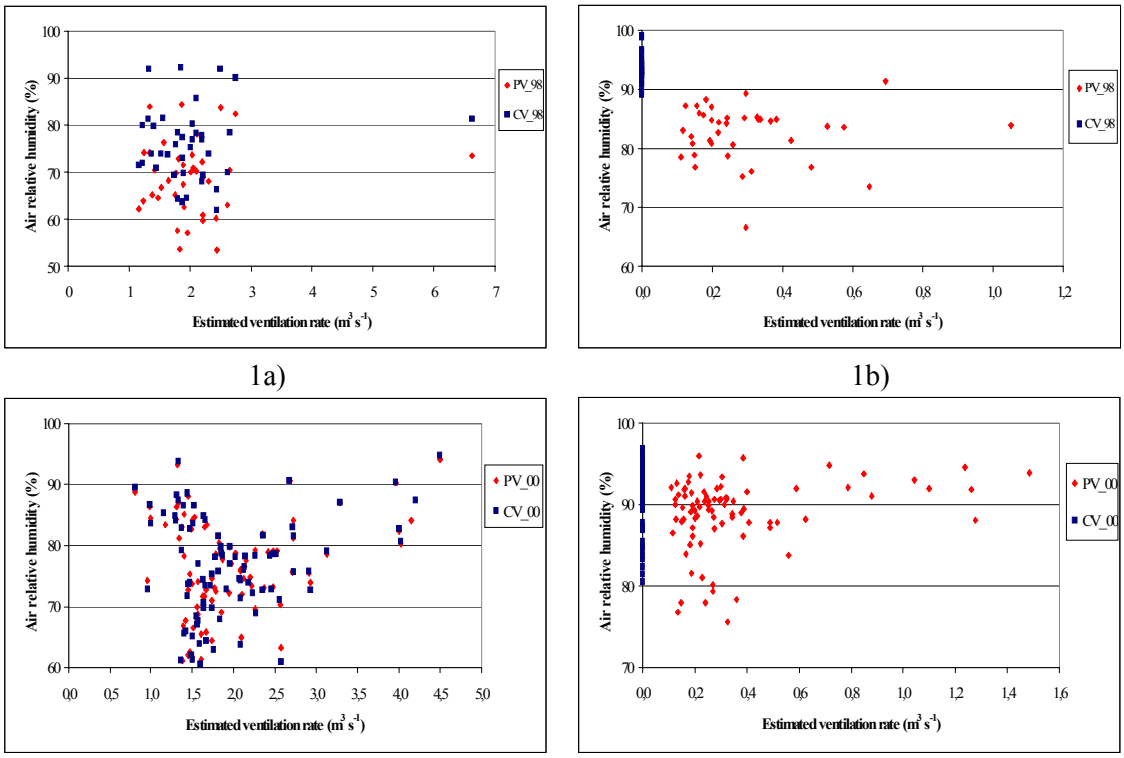



Figure 3.15 – Air relative humidity *versus* the estimated ventilation rate for 1998 (1) and 2000 (2), for day (a) and night (b) periods

During the day, for both years, the air relative humidity was not significantly affected by the air exchange rate. However, during the night in 1998 there is an important difference between the CV and PV greenhouses. In fact, the closed greenhouse, with no air exchange, since leakage was considered negligible due to low night wind speeds (Wang *et al*., 1999b), showed a much higher RH than the ventilated greenhouse. At night in 2000, this effect was not so marked, as already explained, but it still caused some RH reduction in the ventilated greenhouse, with some values lower than 80%. There is no doubt that greenhouse humidity is dependent on ventilation, as shown by the differences found in the CV and PV greenhouses, but we could not say much about the influence of the ventilation rate itself, since the range of variation was small.

Another important aspect that defines the ventilation efficiency is the air distribution and uniformity inside the greenhouses and around the crop, but again we could not analyse this, since we only had one measuring point in the centre of the greenhouse. However, we keep in mind that the highest ventilation rate is not always the best criterion to evaluate ventilation performance (Bartzanas *et al*., 2004; Ould

Khaoua *et al*., 2006) and also that air mixing is incomplete which affects the uniformity of microclimate conditions (Bailey, 2000a; Soni *et al*., 2005; Ould Khaoua *et al*., 2006).

#### 3.3.2.4 Soil temperature

In the climate model chosen as the basis for this thesis (Chapter 4), the growing medium and soil are separated on the basis of the existence or not of plants and the consequent differences in moisture content and shading caused by the crop. In these experiments plants were grown on soil, and at this point, for simplicity we will assume the soil and the growing medium as a whole.

The soil temperature varies with depth and time and is determined by the soil thermal properties, which are dependent on the water content and mineral composition (Thunholm, 1990). During the 1998 experiments the sensors to measure the soil temperature were located at three depths (5, 20 and 50 cm) while in 2000 they were at six depths (surface, 1, 5, 11, 20 and 50 cm). The layer thickness and the location of the sensors during the 2000 experiments were defined by the inputs required for the climate model.

A previous analysis of the measured surface temperature showed a high influence of solar radiation. During the day it reached very high values (> 50ºC) indicating the sensor was directly exposed to solar radiation, resulting in an incorrect soil surface temperature.

One of the simplest methods to predict soil temperature is by numerical modelling based on air temperature (Persaud and Chang, 1983; Thunholm, 1990). Based on the simple assumption that the soil surface temperature should be around the air temperature and the value of soil temperature measured at 1 cm depth, an approach was used to obtain a mathematical relation, which permitted to correct the original surface temperature. Data of soil surface temperature, the values at 1 cm depth and the air temperature, recorded during periods with no solar radiation, were related using a statistical package (TableCurve 3D). The equation obtained is presented below (n = 3152, $r_a^2 = 0.97$ and $RMSE = 0.578$):

$$t_{Ssurf} = 42.750 + 0.011 t_{ia}^2 - \frac{115.927}{t_{S1}^{0.5}} \tag{3.14}$$

The original surface temperatures were then corrected using this equation and the values obtained were assumed to correctly represent the soil surface temperature.

The soil temperature characteristics during the experimental work at the different depths for the two years are shown in Tables 3.14 and 3.15.

Table 3.14 – Soil temperature (ºC) during 1998 experiments

| | $t_{S20}$_CV | $t_{S5}$_PV | $t_{S20}$_PV | $t_{S50}$_PV | $t_{S20}$_E |
|---|---|---|---|---|---|
| Max. | 27.4 | 30.5 | 28.6 | 26.5 | 30.6 |
| Min. | 16.7 | 12.5 | 16.7 | 17.5 | 11.7 |
| Mean | 21.6 | 21.3 | 22.0 | 21.6 | 21.0 |

Comparison of soil temperatures between the CV and PV houses and the exterior (E), at 20 cm depth, shows the maximum and minimum values occurred outside the greenhouses, which was expected since this soil was completely exposed to the external climatic conditions. The mean values were very similar in both greenhouses, which is in agreement with previous work by Meneses *et al*. (1994). Soil temperature tends to be less variable at greats depths, due to the high thermal capacity, and this is indicated by thermal amplitude (9ºC for $t_{S50}$, 11.9ºC for $t_{S20}$ and 22ºC for $t_{S5}$). The temperature measured at 5 cm presented a daily evolution that followed the air temperature (Abreu, 2004).

Table 3.15 – Soil temperature (ºC) during 2000 experiments

| | $t_{S20}$_CV | $t_{Ssurf}$_PV | $t_{S1}$_PV | $t_{S5}$_PV | $t_{S11}$_PV | $t_{S20}$_PV | $t_{S50}$_PV | $t_{S20}$_E |
|---|---|---|---|---|---|---|---|---|
| Max. | 27.6 | 40.7 | 34.5 | 30.1 | 27.0 | 26.2 | 25.1 | 28.9 |
| Min. | 15.5 | 9.3 | 11.3 | 13.4 | 15.5 | 16.4 | 17.9 | 11.9 |
| Mean | 20.6 | 20.2 | 19.1 | 19.4 | 20.0 | 20.2 | 20.3 | 19.3 |

During 2000 the same behaviour was identified for the soil temperature at 20 cm, and again the means were very similar, varying between 19.3 (E) and 20.6ºC (CV). Again the lowest thermal amplitude was at 50 cm and increased as the depth decreased. In fact, $t_{surf}$, $t_{S1}$ and $t_{S5}$ presented thermal amplitudes of 31.4, 23.2 and 16.7ºC, again reflecting the air temperature variation.

In both years the minimal value at 20 cm was near 16ºC, which is higher than 14ºC suggested by Papadopoulos (1991) and 15ºC mentioned by Groenewegen (1999), as the minimum soil temperature for tomato crops.

#### 3.3.2.5 Cover temperature

Measuring the greenhouse cover temperature is difficult due to the transparency of cover materials and the effects of solar and thermal radiations and air movement on

the cover surface. A sensor like an exposed thermocouple junction is significantly affected by solar and thermal radiations and the measured values need to be corrected. Papadakis *et al*. (1992) suggested a correction factor to exclude the effect of solar radiation when SR > 120 W $m^{-2}$, with a low $r^2$ of 0.54. Later, Abdel-Ghany *et al*. (2006) presented another expression that includes also the thermal radiation effect. The correction factor is expressed by the following equation ($r^2$ = 0.92), where SR is the solar radiation in W $m^{-2}$.

$$\Delta t = -0.0922 + 2.9(1 - e^{-0.003SR}) \quad (3.15)$$

Primary analysis of the results showed an overestimation of the cover temperature especially during the day, which means it was mainly due to the effect of solar radiation. Since the correct cover temperature is an essential parameter for the air energy balance, data were corrected using the method proposed by Abdel-Ghany *et al*. (2006). This method consists of obtaining a correction factor ($\Delta t$) to subtract from the value measured by the thermocouple junction attached directly on the cover surface. This was considered an appropriate procedure since it was obtained for the same type of sensors used in our experimental work.

The following results presented were obtained after applying the correction. Some data are missing before day 109 in 1998 and between days 163 and 195 in 2000, due to technical problems with the sensors and recording equipment. Table 3.16 shows the maximum differences between cover temperatures of the two greenhouses during the two years.

Table 3.16 – Maximum cover temperature differences (ºC) between the CV and PV greenhouses

| Year | Date | day | night | 24 h |
|---|---|---|---|---|
| **1998** | 18 April – 3 May | 2.5 | 0.6 | 1.1 |
| | 4 May – 1 June | 2.5 | 0.7 | 1.1 |
| | 2 – 17 June | 2.4 | 0.3 | 1.1 |
| | 18 – 30 June | 2.2 | 0.6 | 1.0 |
| | 18 April – 30 July | 2.5 | 0.7 | 1.1 |
| **2000** | 1 March – 10 May | 0.8 | 0.9 | 0.8 |
| | 17 – 30 May | 1.4 | 1.7 | 1.5 |
| | 1 March – 27 July | 1.5 | 1.7 | 1.5 |

This Table shows that differences during the day and night periods had an inverse behaviour during the two years; during 1998 the maximum differences occurred during the day, while during 2000 the opposite happened. On a daily basis the CV greenhouse presented, in general, a slightly higher cover temperature than the PV house,

with the maximum differences of about 1.1ºC in 1998 and between 0.8 and 1.5ºC in 2000.

During the day, ventilation management was the same in both greenhouses. The higher differences during 1998 could be caused by sensor location that could cause different exposure to solar radiation and the consequent differences in heat gain. During the night, the differences were so small, that confirm the assumption made before concerning the solar radiation influence. However, during the periods with nocturnal ventilation, only in the PV greenhouse (until the end of May) a higher difference was expected in the cover temperature of the two greenhouses due to the higher heat losses caused by the air exchange in the PV greenhouse; see section 3.3.2.1 concerning the air temperature.

During 2000, the differences were very similar during the day and night periods, being slightly higher during the night and this could be explained by the different ventilation management. The highest difference was 1.7ºC and again higher in the CV greenhouse, which was expected since the heat removed by ventilation also influences the cover energy balance. However, a t-test analysis showed no significant differences between cover temperatures of the two greenhouses in both years (Table 3.17).

Table 3.17 –Cover temperatures ( $\bar{x} \pm se$ ) measured in the CV and PV greenhouses for the periods between 18 April and 1 June 1998 and 1 March and 30 May 2000

| | | CV Greenhouse | PV Greenhouse | P |
|---|---|---|---|---|
| **1998** | Day | 24.2 ± 0.7 | 23.0 ± 0.6 | 0.199 |
| | Night | 12.8 ± 0.3 | 12.4 ± 0.3 | 0.269 |
| | 24 h | 17.1 ± 0.3 | 16.4 ± 0.3 | 0.129 |
| **2000** | Day | 23.1 ± 0.5 | 22.9 ± 0.5 | 0.778 |
| | Night | 12.2 ± 0.3 | 11.8 ± 0.3 | 0.335 |
| | 24 h | 16.5 ± 0.2 | 16.1 ± 0.2 | 0.226 |

* Significant differences P < 0.05, $\bar{x}$ - mean, $se$ - standard error

Figure 3.16 shows the evolution of the cover temperature during the night, day and 24 h periods over the whole period of the experiments. Figures 3.16 1a) and 2a) show that the cover temperature during the night changed between 6 and 19ºC, being slightly higher in the CV greenhouse, except between days 154 and 169 in 1998 and between days 60 and 100 in 2000, when the temperatures were almost coincident. In fact, the nocturnal ventilation did not significantly decrease the cover temperature and this is exactly the same as happened with the air temperature.

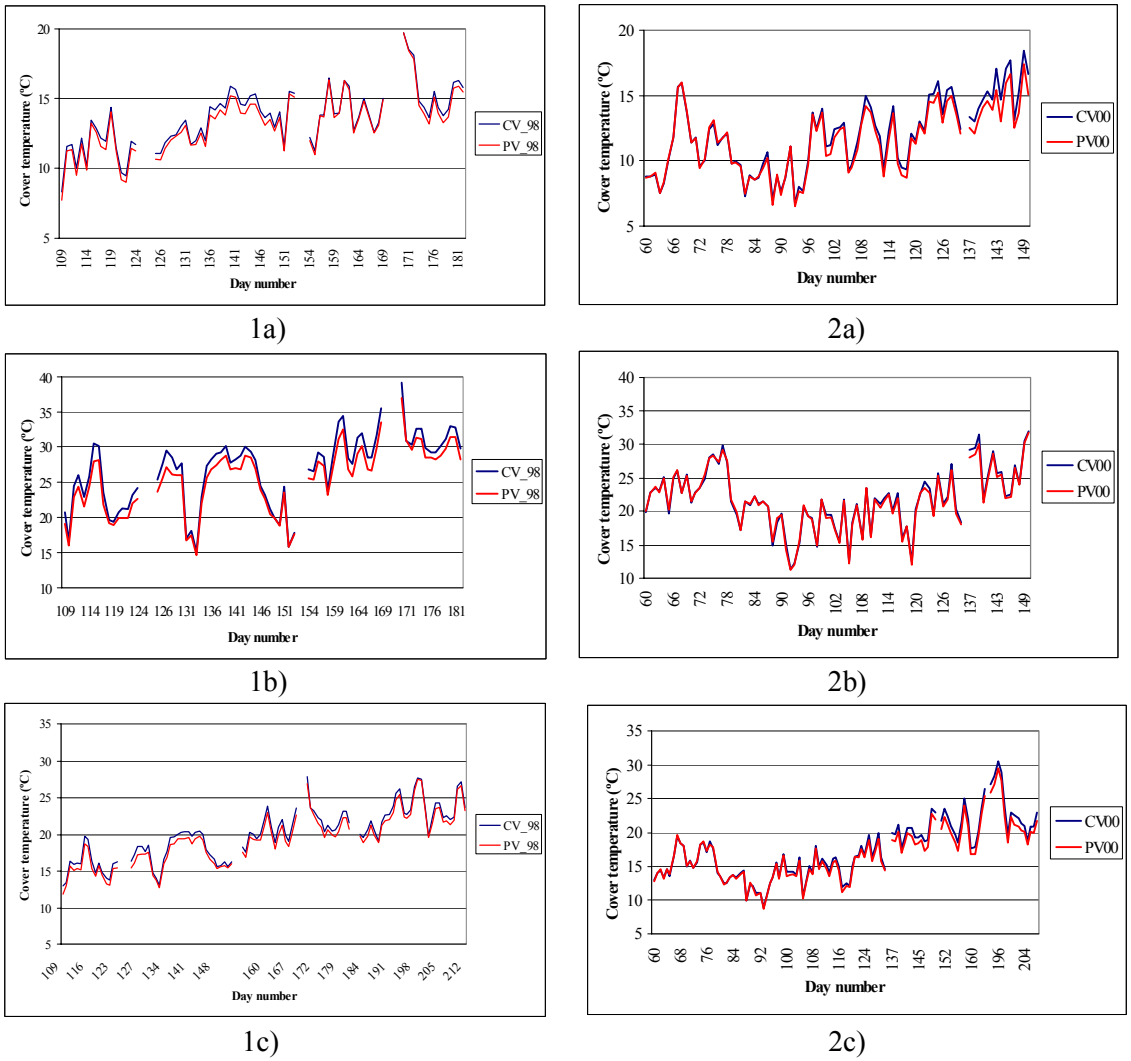



Figure 3.16 - Mean cover temperature for 1998 (1) and 2000 (2) during the night (a), during the day (b) and over 24 h periods (c)

Figures 3.16 1b) and 2b) represents the evolution during the day and it confirms that in 2000, the two greenhouse cover temperatures were very similar, while during 1998 it was higher for the classical ventilated greenhouse. On a daily basis (Figures 3.16 1c and 2c) the cover temperature varied between 10 and 30ºC, being slightly higher during 2000.

### 3.3.2.6 Crop temperature

As mentioned in the previous chapter, leaf temperature was measured by using infrared thermometers and considered as the crop temperature. It is well known there are difficulties in measuring the crop temperature since different parts of the plant may

have different temperatures, depending on the organ (leaf, fruit, flower, stem) and its orientation with respect to the incident solar radiation and air flow (Dayan *et al*., 2004).

During the 1998 experiments, leaf temperature was measured only in the PV greenhouse while in 2000 it was measured in both greenhouses. Figure 3.17 shows the evolution of crop and air temperatures between 7 May and 30 July 1998. In general the crop temperature was always lower than the air temperature. As expected the maximum difference between the air and crop temperatures (5.6ºC) occurred during the day, since plant transpiration is high and reduces leaf temperature. We can also observe the air/crop temperature difference increased with time, which is explained by the solar radiation increase, which is an important factor in inducing transpiration. During the night, the maximum difference between air and crop temperatures was 1.7ºC. This is an important parameter, since depending on the air humidity, it can lead to the occurrence of condensation on leaf surfaces.

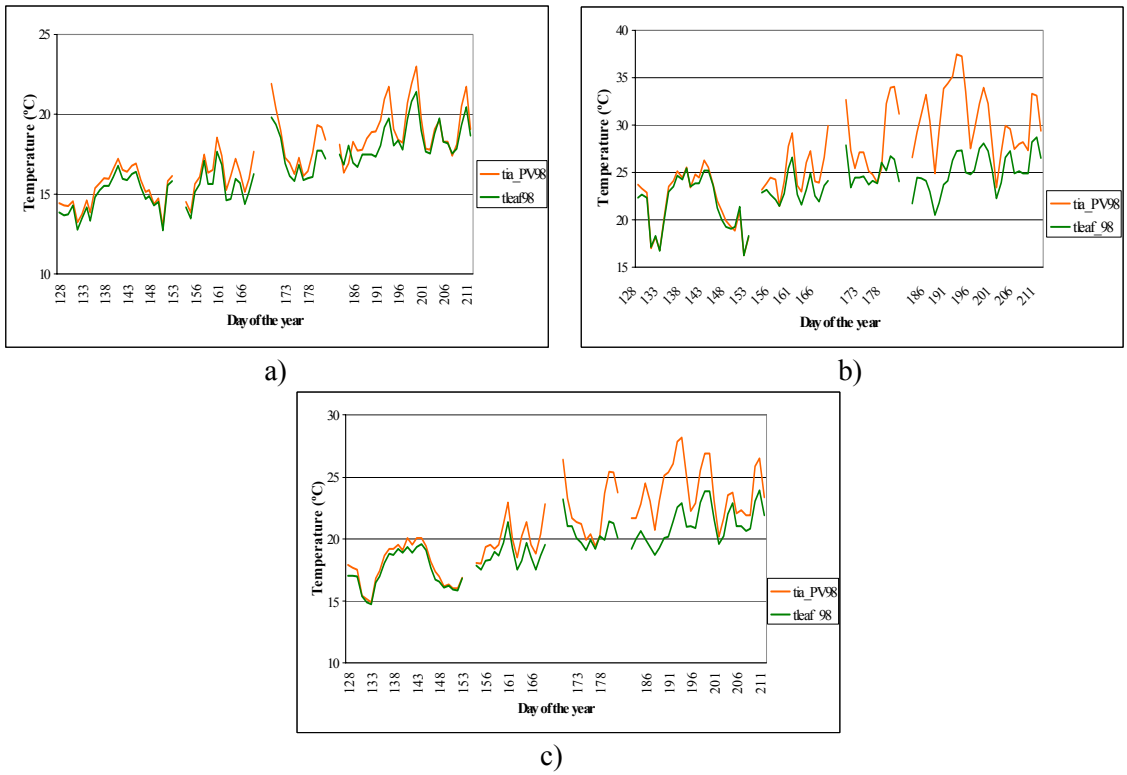



Figure 3.17 - Mean crop temperature during the night (a), the day (b) and over 24 h (c) between 7 May and 30 July 1998

The corresponding values recorded during the 2000 experiments are shown in Figure 3.18. Also presented are the mean air-crop temperature differences as a function of solar radiation, for both greenhouses. Figure 3.18(a) shows that the crop temperature in the CV greenhouse was higher than in the PV house, until the end of May (when

nocturnal ventilation in the PV greenhouse was ended). This may be explained by the higher air exchange rate which induces high heat exchange by convection inside the PV greenhouse. In fact, the maximum difference in crop temperatures recorded in both greenhouses was found in this period (2.8ºC), and it decreased after the ventilation became equal in both greenhouses (0.7ºC). A statistical analysis showed significant differences between the crop temperatures in the two greenhouses during the period with different ventilation management, but non significance differences at a confidence level of 95%, were found when the ventilation managements were the same.

Figure 3.18(b) shows that, during the day the crop temperature in the CV greenhouse again presented higher values than in the PV house, with a maximum difference of 3.3ºC. This was unexpected, since all energy balance components were approximately the same. In fact, it has already shown that the air temperatures were similar in both greenhouses (section 3.3.2.1). As mentioned before leaf temperature is difficult to measure and we believe this difference can be explained by different leaf orientation that could have higher heat gains due to solar radiation. Of course, the daily means reflect the behaviour mentioned and crop temperature in the CV greenhouse was higher than in the PV house, Figure 3.18(c).

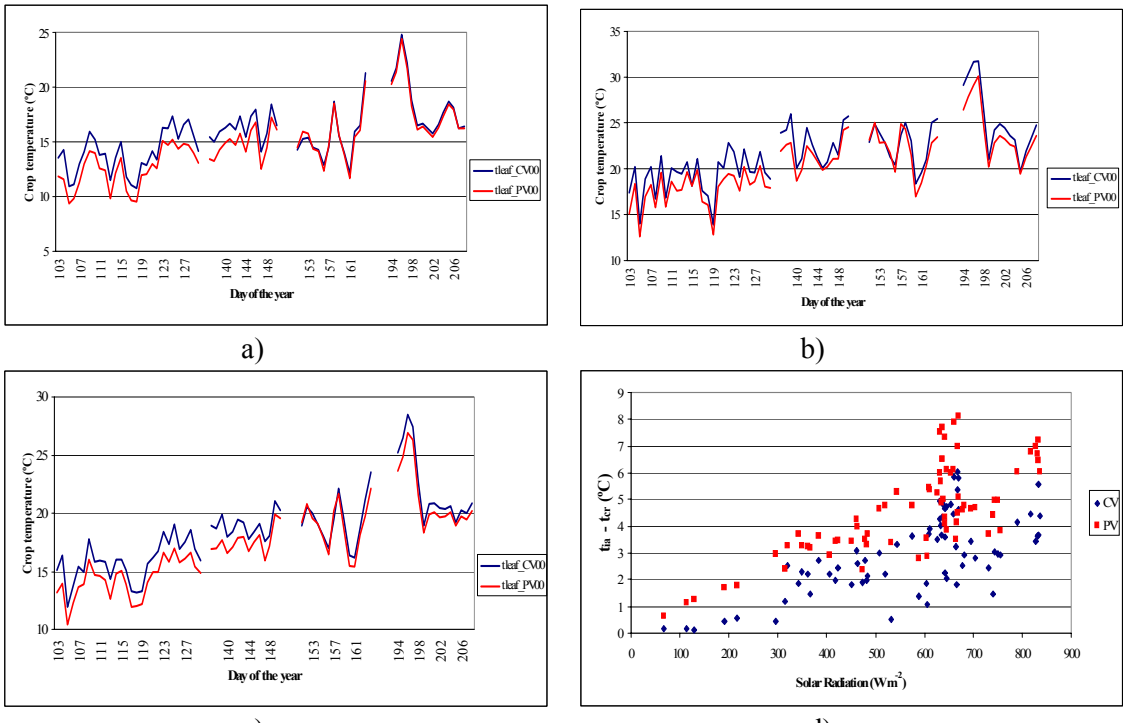



Figure 3.18 - Mean crop temperature during (a) the night, (b) the day, (c), over 24 h and (d) the air to crop temperature difference *versus* solar radiation during the day, for the period between 13 April and 27 July 2000

Figure 3.18(d) presents the temperature difference between the air and crop as a function of solar radiation for both greenhouses. The higher temperature differences for the PV greenhouse are evident and also that they increase with solar radiation, as mentioned previously. In both greenhouses, the crop temperature is several degrees lower than the air due to transpiration, which is in agreement with Boulard *et al.* (1991) and Papadakis *et al*. (1994). As mentioned, the differences between greenhouses may be explained by the leaves orientation, since the air temperatures were very similar and sensors calibration showed no significant differences.

In both years, the mean crop temperature was never higher than 30ºC, which is the limit beyond what plants can suffer adverse effects (Fuchs and Dayan, 1993).

#### 3.3.2.7 Soil moisture content

Soil moisture content was measured during the 2000 experiments as mentioned in Chapter 2. Sensors were located in three different places at a depth of 20 cm and all the measured values were analysed together. The soil moisture content changed between 0.305 and 0.418 $cm^3$ water/$cm^3$ soil, with a mean value of 0.346 and a standard deviation of 0.020 with n=6531. These values are in agreement with those given by Rawls *et al*. (1992) for the soil field capacity characteristic of this soil (0.326-0.466). In fact, during all experiments the soil moisture content was characterised by values that guaranteed tomato plants did not suffer water stress. This was confirmed by the drainage water coming out from the culture system and collected in the rain-o-matic gauge in accordance with Nederhoff (1998).

Soil moisture content is an important property since it directly influences not only the crop, but also the soil temperature and consequently the air temperature and also humidity due to evaporation. Cascone and Arcidiacono (1994) have shown that higher soil moisture content causes an increase in minimum soil temperature and a decrease in maximum soil temperature, explained by increase in heat capacity.

#### 3.3.2.8 Leaf area index (LAI)

The leaf area index ($\bar{x} \pm sd$) obtained for the two years is presented in Figure 3.19. This index represents leaf area in relation to the cropped soil area ($m^2$ $m^{-2}$) and is an important parameter for the climate model since it influences the convective heat

exchange between crop and greenhouse air, and the latent heat balance due to crop transpiration.

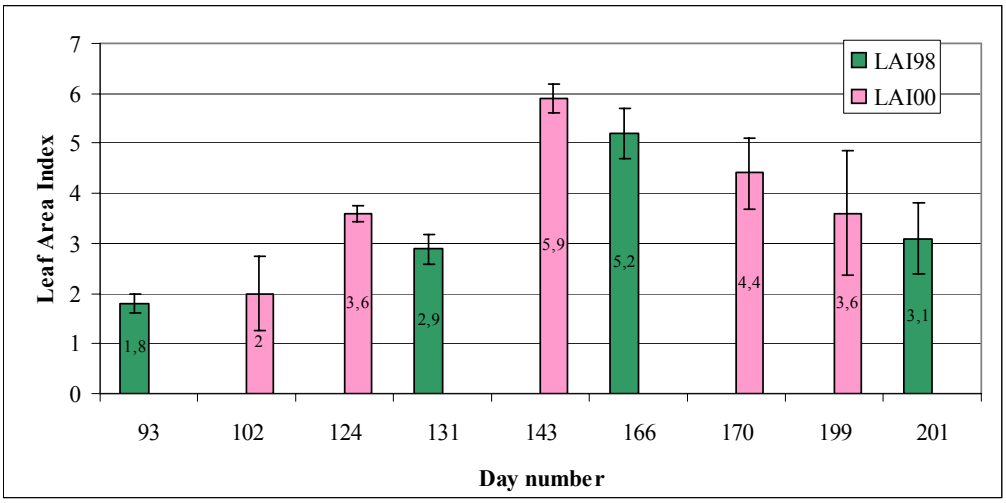



Figure 3.19 – Mean leaf area index measured during 1998 and 2000 experiments (I symbol indicates standard deviation)

Concerning the LAI in 1998, it was approximately quantified using a relation based on the leaf surface and the dry weight (Abreu, 2004). In 2000, LAI was measured directly by destructive methods using 3 plants, in each collecting date, as explained in Chapter 2. As expected the LAI increased with time and reached a maximum of 5.9 by the third week of May, corresponding to the maximum vegetative vigour of the crop. This value is in accordance with that obtained by Zhang *et al*. (1997) for a tomato crop in an unheated greenhouse. Abreu (2004) developed some models to predict LAI either as a function of the plant stage or the leaf dry weight and specific leaf area (leaf area per unit of dry weight).

## 3.4 Conclusions

This chapter presented a brief description of the greenhouse climate parameters considered as the most influent for greenhouse tomato growth and for *B. cinerea* development. A more detailed review concerning the fundamentals of natural ventilation was presented. This is justified by the main objective of this thesis, which is to study the effect of the ventilation management on the greenhouse microclimate conditions and the consequent influence on the occurrence of *B. cinerea*.

Experimental microclimate parameters recorded over the two years in two greenhouses with different ventilation management were presented and analysed. The

objective was to investigate if nocturnal ventilation caused significant differences in the microclimate conditions. It was shown that greenhouse air temperature was not significantly influenced by the night ventilation management. On the contrary, a significant reduction of air humidity occurred in the nocturnally ventilated greenhouse, even with the unfavourable outside conditions that occurred during the spring of 2000. It was shown that soil and cover temperatures were not significantly influenced by nocturnal ventilation while crop temperature was higher in the close greenhouse than in the ventilated one during the night.

These are very important results, which show that nocturnal ventilation is a technique that can be used in unheated greenhouses without causing additional problems for the crop, since it did not reduce air temperature and showed positive effects in lowering the humidity, which can contribute to diminishing some disease attacks.

# 4. Greenhouse climate modelling

This chapter includes a brief literature review of the fundamentals of how the greenhouse climate is created and on greenhouse climate calculation models. A description is given of the physical climate model used in this research, how it was tested and adapted to simulate the microclimate inside the unheated greenhouses, and how the final climate model was validated by comparison between predicted and measured data.

## 4.1 Fundamentals and climate modelling

The variables forming the greenhouse climate which are the most important from the horticultural point of view are the temperature, humidity and carbon dioxide concentration of the greenhouse air. The air temperature depends on the energy losses and gains occurring at a given moment while the humidity depends on the gains and losses of water vapour. The climate produced in a greenhouse is the result of a complex mechanism involving the processes of heat and mass exchange. Heat exchange occurs as sensible heat exchange by conduction, convection and radiation and as latent heat exchange by condensation, transpiration and evaporation. Mass exchange takes place whenever there is an exchange of latent heat and also by the important process of ventilation. The internal climate is strongly dependent on the outside conditions, especially in unheated greenhouses (Nijskens *et al.,* 1991; Linker and Seginer, 2004). In greenhouse climate models the parameters of the internal climate such as air, soil and crop temperature, and air humidity are calculated using energy and water vapour balances for the various components of the system. An energy balance is the sum of the heat gains and losses, during a certain period of time. The method assumes a steady state and uses the principle of energy conservation, that heat gains are equal to heat losses plus a term referring to the heat storage in the greenhouse, which is function of the inertial thermal of all the components. Using this approach, the inside humidity and temperature can be predicted if the outside conditions and ventilation rate are known. This method also allows the ventilation rate or heating need to be estimated to achieve predefined inside conditions.

Considering greenhouses as solar collectors, which exchange sensible and latent heat with the exterior, Boulard and Baille (1987, 1993), suggested a general equation for the energy balance of an unheated greenhouse:

$$Q_{SRi} - Q_C - Q_{ve\_se} - Q_{ve\_la} - Q_m = 0 \quad (4.1)$$

where $Q_{SRi}$ is the solar radiation heat gain, $Q_C$ the heat exchange through the cover, which includes convective and thermal radiative losses, $Q_{ve\_se}$ is the sensible heat losses due to ventilation, $Q_{ve\_la}$ is the latent heat losses due to ventilation and $Q_m$ represents the heat storage (or extraction) in the greenhouse thermal mass, which in the case of soil grown crops corresponds to the soil itself. Each of these terms is defined by an equation and can be determined experimentally, except the exchanges by convection (Day and Bailey, 1999; Baptista *et al*., 2001b). A detailed review concerning the physical principles of microclimate modification was presented by Bot and van de Braak (1995) and by Day and Bailey (1999).

Inside a greenhouse heat transfer by conduction occurs through the cladding and between layers of the soil. Since cover materials are thin, conduction can be neglected. The soil can be an important factor, since soil will store heat during the day and can be an important heat source during the night (Day and Bailey, 1999). The soil thermal properties are influenced by temperature, moisture content and mineral composition (Monteith and Unsworth, 1990; Navas, 1996). The Fourier law is used to express heat fluxes by conduction as a function of the thermal conductivity and thickness of the material, and temperature difference (Montero *et al*., 1998). Several models have been developed to predict soil temperature (Persaud and Chang, 1983; Papadakis *et al*., 1989a; Thunholm, 1990; Luo *et al*., 1992; Cascone and Arcidiacono, 1994).

Convective heat transfer is one of the most important transfer mechanisms occurring between a solid surface and a fluid, corresponding to the transfer of heat by air moving. Inside a greenhouse heat exchange by convection occurs between the cover material, soil, plants and inside air and also between the cover material and the outside air. Convection can be classified as: 1) free or natural if it results from differences in air density due to temperature differences and 2) forced if it results from a moving airstream. In both cases it depends on the greenhouse characteristics, external climatic conditions and ventilation management (Roy *et al.*, 2002). In closed greenhouses, the internal air speed is low and the tendency is for free convection, while if relatively high air speed occurs convection usually is forced.

Solar radiation inside a greenhouse depends on the external global solar radiation and on the transmissivity of the cover. It is an important component of the energy balance since it is the main source of heat and is fundamental to plant growth as it directly influences plant photosynthesis and transpiration. Calculations are a complex process, since heat gain due to solar radiation is influenced by several factors, like the sun position, angle of incidence of the radiation, the optical properties of the covering material, and geometry and orientation of the greenhouse (Navas, 1996). Critten (1983) has shown that the most accurate models are those which assume that solar radiation after reaching the cover, is transmitted creating multiple reflections through the greenhouse surfaces. However, these can be simplified when the objective is only to study the contribution of solar radiation in the energy and mass balances of a greenhouse. According to Boulard and Baille (1993) the radiation absorbed by the crop is proportional to inside global solar radiation and hence to the outside global radiation affected by the canopy absorption coefficient for solar radiation.

Heat losses due to long wave thermal radiation are essentially between the sky and soil, plants, structure and covering materials. These losses can be very important if the covering material has high transmissivity to thermal radiation, as with normal polyethylene films. Thermal radiation losses can be calculated by using a simple approximation based on the Stefan-Boltzman law, as a function of the surface emissivity, the atmospheric emissivity (a function of the atmosphere dew point), the transmissivity of the cover material to thermal radiation and the relevant temperatures. More detailed explanations can be found in Navas (1996) and Baptista *et al*. (2001b).

Plant transpiration is influenced, and influences, environmental control techniques such as heating, shading, ventilation, dehumidification or humidification. It is the main process by which plants can control their own temperature. Generally Penman-Monteith equation is used to describe the transfer of water vapour between the leaf and the air as a function of the partial water vapour pressure at saturation at the leaf surface temperature, the water vapour pressure, the aerodynamic and stomatal conductances, and leaf area index (LAI). Usually the Penman-Monteith equation is simplified by introducing the increase in leaf temperature due to solar radiation and by linearizing the relation between saturated vapour pressure and temperature (Monteith, 1973):

$$E = \alpha SR_i + \beta VPD \tag{4.2}$$

where $SR_i$ is the net radiative exchange between the canopy and the environment and *VPD* the vapour pressure deficit inside the greenhouse. Parameters $\alpha$ and $\beta$ are determined as a function of the crop stage or the leaf area index. However, Jolliet (1999) stated that most of those models cannot be used for different climate conditions, crop stages or crop configurations without determining the coefficients for the particular situations.

The latent heat transfer by evaporation from the soil to the air can be neglected when under a full vegetative cover (Seginer, 2002) and when trickle ferti-irrigation is used (Jolliet, 1999; Baptista *et al*., 2005). When existing, evaporation from the soil and condensation from the air to the cover are determined using the convective heat transfer theory of Bowen's assumption and the Lewis relation (Boulard *et al*., 1989).

Water vapour production in greenhouses is high and if no control techniques are used such as ventilation or heating, the formation of condensation on the roof and walls will occur. In unheated greenhouses, with low night temperature and high relative humidity drop-wise condensation on the interior of the plastic covers could be a problem favouring the development of fungal diseases. Baptista *et al*. (2001a) showed that nocturnal ventilation reduced the condensation periods by the decrease of the relative humidity and by the slow increase of inside air temperature during the first hours in the morning.

Interest on greenhouse research increased during the 1970s due to oil crises (Critten and Bailey, 2002), which turned energy saving into an important subject. That can be achieved by using the appropriate environmental control techniques at the right moment. For that climate models are important tools, helping to predict the microclimate conditions inside greenhouses and also enabling the use of automatic control systems, which are the two main objectives of greenhouse climate models. Of course, climate control has the main objective of providing the favourable microclimate conditions for crop growth with the minimum cost. A full description of climate modelling in greenhouses can be found in Bailey (1991).

Empirical climate models are obtained with transfer functions which describe the relations between the variables by means of identification techniques, without considering the physics of the process involved, and will not be analysed in detail. Analytical climate models, result from a detailed description of the heat and mass balances inside the greenhouse and can be used either to study the physical phenomena which occur in a greenhouse or for systems control. These models can be static or

dynamic depending on the response time and on the consideration or not of the heat storage capacity of the system components. Depending on the number of physical processes involved these models can be simple or complex. The increasing complexity of greenhouse climate models has occurred because of computer science development and the availability of personal computers.

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

Dynamic models are important for simulating the greenhouse response on a small timescale, which require the proper representation of the heat exchange processes between the interacting components. The heat and mass transfer coefficients are functions of the system variables and it is important that they are formulated under relevant conditions of the greenhouse situation (Bailey, 1991). Most of these models are complex, based on heat flux equations for the several components. Due to the high complexity, various assumptions are usually made in order to simplify the solution, such as the perfectly stirred tank and the big leaf approaches. Several authors developed simple dynamic greenhouse climate models (Boulard and Baille, 1987, 1993; Boulard *et al*., 1996; Perales *et al*., 2003; Perdigones *et al*., 2005; Baille *et al*., 2006; Coelho *et al*., 2006; Harmanto *et al*., 2006) while others presented complex dynamic models (Bot, 1983; Navas, 1996; Zhang *et al*., 1997; Pieters and Deltour, 1997; Navas *et al*., 1998; Wang and Boulard, 2000; Abdel-Ghani and Kozai, 2006a; Singh *et al*., 2006).

In fact the climate models mentioned so far contain sub-models describing the different physical phenomena occurring between the greenhouse components. Several studies have been published which consider separately, the particular aspects of the heat balances. For instances, studies relative to ventilation have been performed by Kittas *et al*. (1996), Baptista *et al*. (1999), Roy *et al*. (2002), Boulard *et al*. (2004) and Teitel *et al*. (2005). Condensation has been studied by Geoola *et al*. (1994), Wei *et al*. (1995), Pieters (1996), Seginer and Zlochin (1997) and Campen and Bot (2002); transpiration by Stanghellini (1987), Yang *et al.* (1990), Jolliet and Bailey (1992), Baille *et al.*

(1994), Jolliet (1994), Stanghellini and de Jong (1995), Baptista *et al*. (2000a, 2005), Fatnassi *et al*. (2004) and Fuchs *et al*. (2006); solar radiation by Critten (1983, 1987, 1993), Rosa *et al*. (1989), Miguel *et al*. (1994) and Medrano *et al*. (2005); thermal radiation by Silva and Rosa (1987), Papadakis *et al*. (1989b), Kittas (1994), Vollebregt and van de Braak (1995), Gusman *et al.* (1996) and Abdel-Ghani and Kozai (2006b) and the crop by Papadakis *et al*. (1994), Brisson *et al*. (2003) and Abreu (2004).

As mentioned in Chapter 3 new techniques such as computational fluid dynamics (CFD) are now being used for modelling the greenhouse climate (Bartzanas *et al*., 2004; Boulard *et al*., 2004; Molina-Aiz *et al*., 2004; Montero *et al*., 2005; Fatnassi *et al*., 2006; Ould Khaoua *et al*., 2006). Also, an even more recent technique, the lattice model, which uses a numerical approach and can also simulate fluid dynamics was developed in the last decade of the 20$^{th}$ century and has been used by Jiménez-Hornero *et al*. (2006).

Also, some greenhouse climate models developed by statistical methods can be found in literature (Davis, 1984; Chalabi and Fernández, 1994; Litago *et al*., 1998, 2000, 2005). These empirical models are based on the system identification and are a complementary approach to physical process models, since they are built by observing input and output data, but considering the knowledge of the physics of the system (Litago *et al*., 2005). Fuzzy modelling, also based on the system identification approach, has been used by Kim *et al*. (2004) to model leaf wetness duration and by Salgado and Cunha (2005) for modelling the climate of a greenhouse.

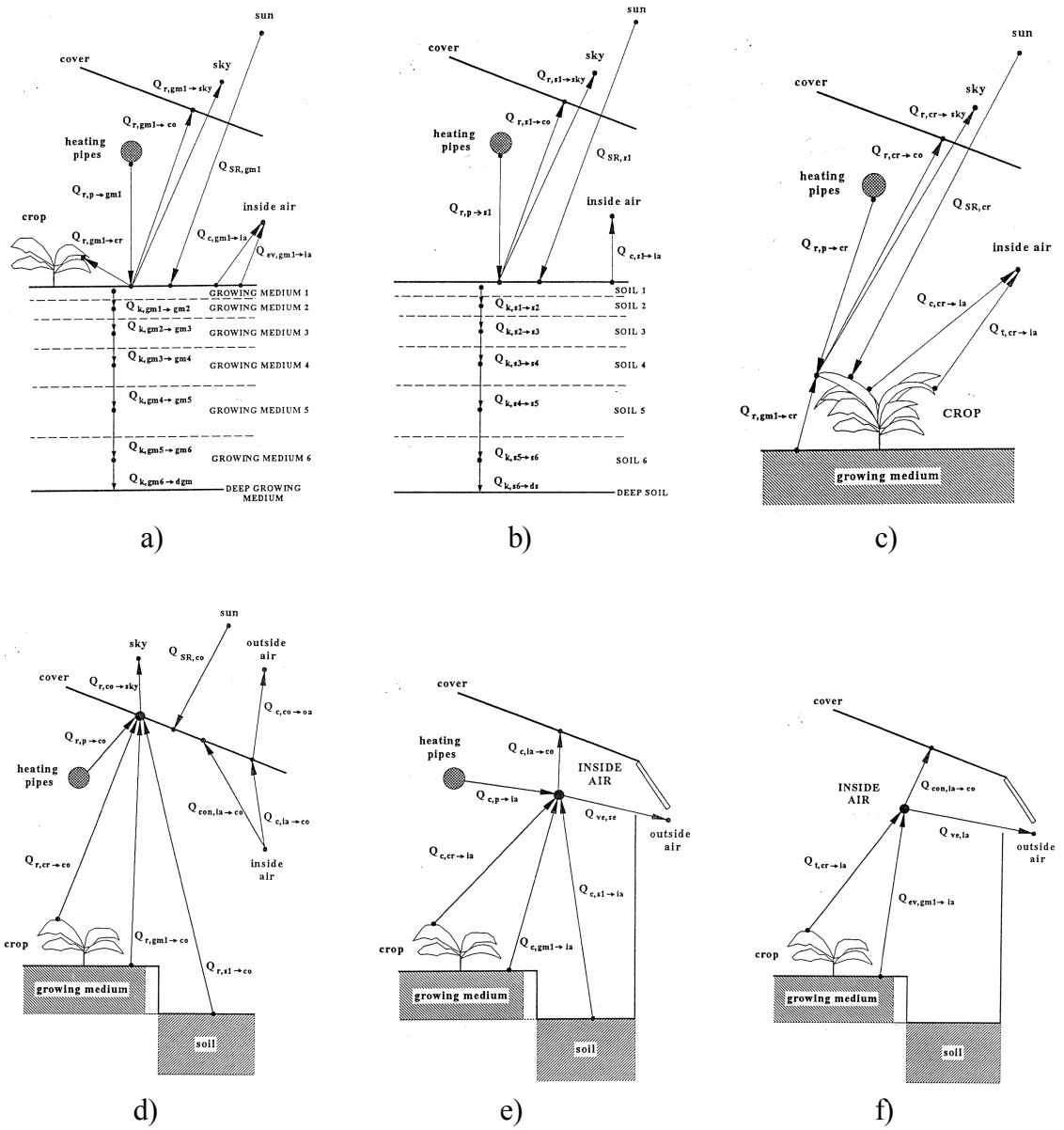
Most of the greenhouse climate models are specific for a greenhouse type, crop, region and weather conditions. Models are formulated and validated for those specific conditions and it is not possible to directly extrapolate them to other different conditions, since they may produce erroneous predictions. In order to use them in different conditions, calibration of the models coefficients should be done by means of experimental work, followed by the validation of the adapted model.

## 4.2 Description of the climate model

In this section a brief explanation of the climate model chosen as the basis to predict the greenhouse microclimate conditions will be given. The dynamic model was developed and validated by Navas (1996) for a Mediterranean greenhouse with a gerbera crop. This model was used as the basis but some modifications were necessary

to adjust it to the specific conditions of the experimental greenhouses used for this investigation. These aspects will be explained in the next section.

Figure 4.1 provides a schematic representation of all the energy fluxes between the greenhouse components.




a) growing medium, b) soil, c) crop, d) cover, e) air sensible heat and f) air latent heat. c–convection, co–cover, con–condensation, cr–crop, dgm–deep growing medium, ds–deep soil, ev–evaporation, gm-growing medium, ia-inside air, k-conduction, la-latent heat, oa-outside air, p-heating pipes, Q-heat flux, r-thermal radiation, s-soil, se-sensible heat, SR-solar radiation, tr-transpiration, ve-ventilation.

Figure 4.1 – Schematic representation of the energy fluxes included in the greenhouse model (from Navas, 1996).

In the model, which is basically quasi-one-dimensional and single layer, the greenhouse is divided in five components: growing medium, soil, crop, cover and inside air. The energy fluxes between the components of the greenhouse model are described

by the exchange of sensible heat, latent heat and radiation, per unit area. The dynamic characteristics of the model arise from consideration of the heat storage in the growing medium and soil, which requires these components to be sub-divided into six layers to describe their thermal capacities correctly.

Energy balance equations are formulated for each of the five greenhouse components. The growing medium, soil, crop and cover are characterised by their temperature, so only thermal balance equations are defined. On the contrary, the inside air is defined by the temperature and humidity, so thermal and moisture balance equations are formulated for this component. As a result, the model is composed of sixteen energy balances, making up a set of six algebraic (thermal balances of superficial growing medium and soil, crop and cover, and the thermal and moisture balances of the inside air) and ten first-order differential (thermal balances of growing medium and soil, from layer 2 to layer 6) equations. The fourth-order Runge-Kutta method (initial values method) was used to solve the differential equations numerically, to obtain the temperatures for the several layers. The general heat balance equations are presented below (see notation section for definition of symbols):

- Sensible heat balances

Growing medium surface

$$Q_{SR,gm1} - Q_{k,gm1\to gm2} - Q_{r,gm1\to cr} - Q_{r,gm1\to co} - Q_{r,gm1\to sky} - Q_{c,gm1\to ia} - Q_{ev,gm1\to ia} = 0 \tag{4.3}$$

Soil surface

$$Q_{SR,s1} - Q_{k,s1\to s2} - Q_{r,s1\to co} - Q_{r,s1\to sky} - Q_{c,s1\to ia} = 0 \tag{4.4}$$

Crop

$$Q_{SR,cr} + \frac{A_{gm}}{A_{cr}} Q_{r,gm\to cr} - Q_{c,cr\to ia} - Q_{r,cr\to co} - Q_{r,cr\to sky} - Q_{tr,cr\to ia} = 0 \tag{4.5}$$

Cover

$$Q_{SR,co} + \frac{A_{gm}}{A_{co}} Q_{r,gm\to co} + \frac{A_s}{A_{co}} Q_{r,s\to co} + \frac{A_{cr}}{A_{co}} Q_{r,cr\to co} + Q_{c,ia\to co} + Q_{con,ia\to co} - Q_{r,co\to sky} - Q_{c,co\to oa} = 0 \tag{4.6}$$

Inside air

$$\frac{A_{gm}}{A_g} Q_{c,gm1\to ia} + \frac{A_s}{A_g} Q_{c,s1\to ia} + \frac{A_{cr}}{A_g} Q_{c,cr\to ia} - \frac{A_{co}}{A_g} Q_{c,ia\to co} - Q_{ve,se} = 0 \tag{4.7}$$

Growing medium (*gm*) and soil conduction (*gm* replaced by *s*) between the several layers

$$Q_{k,gmi\rightarrow gmi+1}=\frac{2k_{gmi}k_{gmi+1}}{k_{gmi}z_{gmi+1}+k_{gmi+1}z_{gmi}}(t_{gmi}-t_{gmi+1}) \qquad i=1\rightarrow 5 \tag{4.8}$$

$$Q_{k,gm6\rightarrow dgm}=\frac{2k_{gm6}}{z_{gm6}}(t_{gm6}-t_{dgm}) \tag{4.9}$$

- Inside air latent heat balance

$$\frac{A_{gm}}{A_g}\frac{Q_{ev,gm1\rightarrow ia}}{\lambda_{gm1}}+\frac{A_{cr}}{A_g}\frac{Q_{tr,cr\rightarrow ia}}{\lambda_{cr}}-\frac{A_{co}}{A_g}\frac{Q_{con,ia\rightarrow co}}{\lambda_{co}}-\frac{Q_{ve,la}}{\lambda_{ia}}=0 \tag{4.10}$$

Each of the heat fluxes is determined using the following equations:

$$Q_{c,gm1\rightarrow ia}=h_{c,gm1\rightarrow ia}(t_{gm1}-t_{ia}) \tag{4.11}$$

$$Q_{c,s1\rightarrow ia}=h_{c,s1\rightarrow ia}(t_{s1}-t_{ia}) \tag{4.12}$$

$$Q_{c,co\rightarrow oa}=h_{c,co\rightarrow oa}(t_{co}-t_{oa}) \tag{4.13}$$

$$Q_{c,ia\rightarrow co}=h_{c,ia\rightarrow co}(t_{ia}-t_{co}) \tag{4.14}$$

$$Q_{c,cr\rightarrow ia}=2LAIh_{c,cr\rightarrow ia}(t_{cr}-t_{ia}) \tag{4.15}$$

$$Q_{r,gm1\rightarrow cr}=\frac{A_{cr}}{A_{gm}}\frac{1}{\frac{1}{\varepsilon_{gm}}+\frac{1}{\varepsilon_{cr}}-1}\sigma(T_{gm1}^4-T_{cr}^4) \tag{4.16}$$

$$Q_{r,gm1\rightarrow co}=(1-\frac{A_{cr}}{A_{gm}})\frac{1}{\frac{1}{\varepsilon_{gm}}+\frac{A_{gm}-A_{cr}}{A_{co}}(\frac{1}{\varepsilon_{co}}-1)}\sigma(T_{gm1}^4-T_{co}^4) \tag{4.17}$$

$$Q_{r,gm1\rightarrow sky}=(1-\frac{A_{cr}}{A_{gm}})\tau_{r,co}\varepsilon_{gm}\sigma(T_{gm1}^4-T_{sky}^4) \tag{4.18}$$

$$Q_{r,s1\rightarrow co}=\frac{1}{\frac{1}{\varepsilon_s}+\frac{A_s}{A_{co}}(\frac{1}{\varepsilon_{co}}-1)}\sigma(T_{s1}^4-T_{co}^4) \tag{4.19}$$

$$Q_{r,s1\rightarrow sky}=\tau_{r,co}\varepsilon_s\sigma(T_{s1}^4-T_{sky}^4) \tag{4.20}$$

$$Q_{r,cr\rightarrow co}=\frac{1}{\frac{1}{\varepsilon_{cr}}+\frac{A_{cr}}{A_{co}}(\frac{1}{\varepsilon_{co}}-1)}\sigma(T_{cr}^4-T_{co}^4) \tag{4.21}$$

$$Q_{r,cr\to sky} = \tau_{r,co}\varepsilon_{cr}\sigma(T_{cr}^4 - T_{sky}^4) \tag{4.22}$$

$$Q_{r,co\to sky} = \varepsilon_{co}\sigma(T_{co}^4 - T_{sky}^4) \tag{4.23}$$

$$Q_{SR,gm1} = \alpha_{SR,gm}\left[\left(1 - \frac{A_{cr}}{A_{gm}}\right) + \frac{A_{cr}}{A_{gm}}e^{-K_{SR,cr}LAI\sqrt{1-\vartheta_{SR,h}}}\right]SR_i \tag{4.24}$$

$$Q_{SR,s1} = \alpha_{SR,s}0.10SR_i \tag{4.25}$$

$$Q_{SR,cr} = \left[\left(1-\varphi_{SR,cr}\right) - \left(1-\varphi_{SR,gm1}\right)e^{-K_{SR,cr}LAI\sqrt{1-\vartheta_{SR,h}}}\right]SR_i \tag{4.26}$$

$$Q_{SR,co} = \alpha_{SR,co}\left[\frac{1}{\tau_{SR,co}} + \varphi_{SR,cr} + \varphi_{SR,gm1}(1 - \frac{A_{cr}}{A_{gm}}) + \varphi_{SR,s}0.10\right]SR_i \tag{4.27}$$

$$Q_{ev,gm1\to ia} = \frac{h_{c,gm1\to ia}}{\gamma_{ia}Le}(RH_{gm1}e_{gm1}^* - e_{ia}) \tag{4.28}$$

$$Q_{co,ia\to co} = \frac{h_{c,ia\to co}}{\gamma_{ia}Le}(e_{ia} - e_{co}^*) \tag{4.29}$$

$$Q_{tr,cr\to ia} = \frac{2LAI\rho_{ia}c_{ia}}{\gamma_{ia}(r_i + r_e)}(e_{cr}^* - e_{ia}) \tag{4.30}$$

$$Q_{ve,se} = \frac{V\rho_{ia}c_{ia}}{A_g}(t_{ia} - t_{oa}) \tag{4.31}$$

$$Q_{ve,la} = \frac{V\rho_{ia}c_{ia}}{\gamma_{ia}A_g}(e_{ia} - e_{oa}) \tag{4.32}$$

The greenhouse is divided in process and boundary components. The variables simulated (process components) by the model are the inside air temperature and relative humidity, the temperatures of the crop, cover, soil and growing medium. The boundary components are the characteristics of the outside air (temperature and relative humidity), wind speed, solar radiation, temperatures of deep growing medium and soil, growing medium and soil moisture contents and the characteristics of the environmental control systems. The model is parameterized by a set of constants relating to geometrical, thermal, optical and other properties of the greenhouse-crop system.

The model simulation time interval is 1 min, which is comparable with the time constants of the model process components with low thermal capacities. A computer programme was written by Navas (1996) in Pascal, which runs on any PC to operate the model, called DPG (Dynamic Performance of Greenhouses). This programme includes

all the necessary code to define the heat fluxes established in the model and mathematical algorithms to solve the greenhouse energy balances.

Results of simulation at instant t are influenced by the results of simulation at instant t-1, which means that in the beginning it is necessary to introduce a set of initial conditions (1). To run the model it is also necessary to provide values for the boundary conditions at the time intervals (2) and the constant parameters (3) relating to the greenhouse/crop system. The boundary conditions data are compiled in the DATA_* files, and during each simulation time interval (1 min) their values are considered constants.

Figure 4.2 presents the basic flow chart of DPG program. It is divided into two modules: FIX_GH and DS_GH. The first is where the user introduces information about the greenhouse, crop, growing medium and soil properties, the ventilation facilities, and also the initial values of the simulated variables; the second is the simulator of the greenhouse climate. This last module uses the information given before by the user and also the DATA_* files (24 for each day), which have the boundary conditions variables for each minute. Module DS_GH generates RESU_* files for each hour, which have the results of the simulated variables for the model (24 in total). A full description of all equations, the model and the DPG programme was given by Navas (1996).

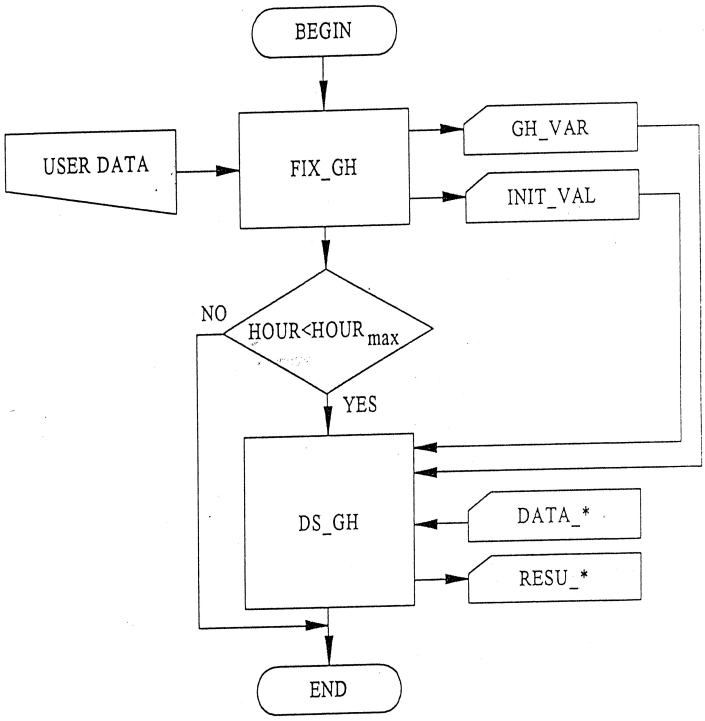



Figure 4.2 – Basic flow chart of the DPG program (Navas, 1996; Navas *et al*., 1996)

## 4.3 Modification of the climate model

Since the climate model was developed for different conditions than those which occurred in our work, it was necessary to test it with the new conditions and make the adjustments as necessary. The methodology followed to adjust the climate model was:

1. To identify the problems by using the original climate model with data recorded during the 1998 experiments and with some calculated parameters which had not been measured (soil moisture content and inside air speed);
2. To modify the model in a systematic way;
3. To compare the results obtained from simulations with the model before and after the modifications. Some data obtained during 2000 were also used as they were more appropriate to the model inputs;
4. To obtain the final climate model, after all the necessary modifications;
5. To validate the final climate model, with data from both years of experiments. For this the predicted and measured variables were compared for several greenhouse components.

Comparison between predicted and measured values was done graphically to show trends in the data and by using statistical parameters to characterise model performance, such as mean error (*ME*), root mean square error (*RMSE*), adjusted determination coefficient ($r_a^2$) and maximum absolute error.

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

Baptista *et al.* (2000b, 2001c) presented results of simulations for several days in different months based on the external climatic data, and parameters related with the growing medium, the covering material and the crop. The distinction between the growing medium and soil was on the basis of moisture content, considering the soil as the area of dry ground and the growing medium as the wet area, which corresponded to the area occupied by the crop. Since it was a first approximation and due to the inputs of the model, it was necessary to make some assumptions and to estimate a few parameters which had not been measured during the 1998 experiments. The growing medium

moisture content was estimated using methods described by Rawls *et al.* (1992) and Allen *et al.* (1994). The inside air speed was estimated using an expression obtained by linear regression, from data measured in a similar greenhouse, considering the inside air speed as a function of the wind speed and the area of the open vents ($v_{ia}$=0.019+0.031$v_w$+0.003$A$, $r^2$ = 0.72). This method is similar to that used by Wang *et al.* (1999a). A detailed description can be found in Baptista *et al.* (2000b).

Table 4.1 presents the root mean square error and the mean error between the predicted and measured values for each of the analysed days and Figure 4.3 shows the results obtained for some of the greenhouse components for day 5 June 1998.

Table 4.1 – Root mean square error (*RMSE*) and mean error (*ME*) between the values given by the original model and those measured

| | | **29.04.98** | **09.05.98** | **15.05.98** | **20.05.98** | **05.06.98** | **21.06.98** |
|---|---|---|---|---|---|---|---|
| **$t_{ia}$ (ºC)** | *RMSE* | 1.27 | 2.45 | 1.14 | 2.31 | 0.87 | 1.93 |
| | *ME* | 0.01 | 1.27 | 0.25 | 1.05 | 0.48 | 1.66 |
| **$RH_{ia}$ (%)** | *RMSE* | 4.60 | 10.43 | 11.01 | 8.30 | 8.10 | 9.34 |
| | *ME* | 2.05 | 3.35 | 8.01 | -2.13 | -0.69 | -7.64 |
| **$t_{crop}$ (ºC)** | *RMSE* | 2.66 | 7.02 | 4.18 | 5.46 | 4.96 | 7.34 |
| | *ME* | 1.20 | 5.19 | 2.74 | 4.04 | 3.46 | 5.48 |
| **$t_{cover}$ (ºC)** | *RMSE* | 1.27 | 2.32 | 1.61 | 2.16 | 1.61 | 2.20 |
| | *ME* | -0.16 | -1.32 | -0.79 | -1.14 | -0.32 | -0.48 |
| **$t_{gm3}$ (ºC)** | *RMSE* | 0.52 | 4.41 | 3.42 | 3.88 | 2.99 | 3.11 |
| | *ME* | 0.30 | 2.41 | 1.57 | 2.32 | 1.54 | 1.19 |
| **$t_{gm5}$ (ºC)** | *RMSE* | 0.28 | 1.59 | 1.38 | 1.34 | 1.02 | 1.43 |
| | *ME* | 0.01 | 0.56 | 0.54 | 0.34 | 0.39 | 0.63 |
| **$t_{s3}$ (ºC)** | *RMSE* | 7.60 | 9.72 | 8.29 | 8.26 | 9.96 | 10.76 |
| | *ME* | 4.52 | 5.84 | 4.94 | 5.18 | 6.54 | 6.82 |

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

The simulated crop temperatures were much higher than the measured values, especially during the day which could be due to an incorrect model estimation of the heat exchange by transpiration. This seems reasonable since the crop characteristics incorporated in the model were for a gerbera crop. The expression to determine stomatal resistance had been experimentally obtained by Navas (1996). Others aspects that could

contribute to the results were the expression to determine the convection heat transfer coefficient, the leaf area index and the proportion of the growing medium which was receiving solar radiation and then emitted thermal radiation to the crop.

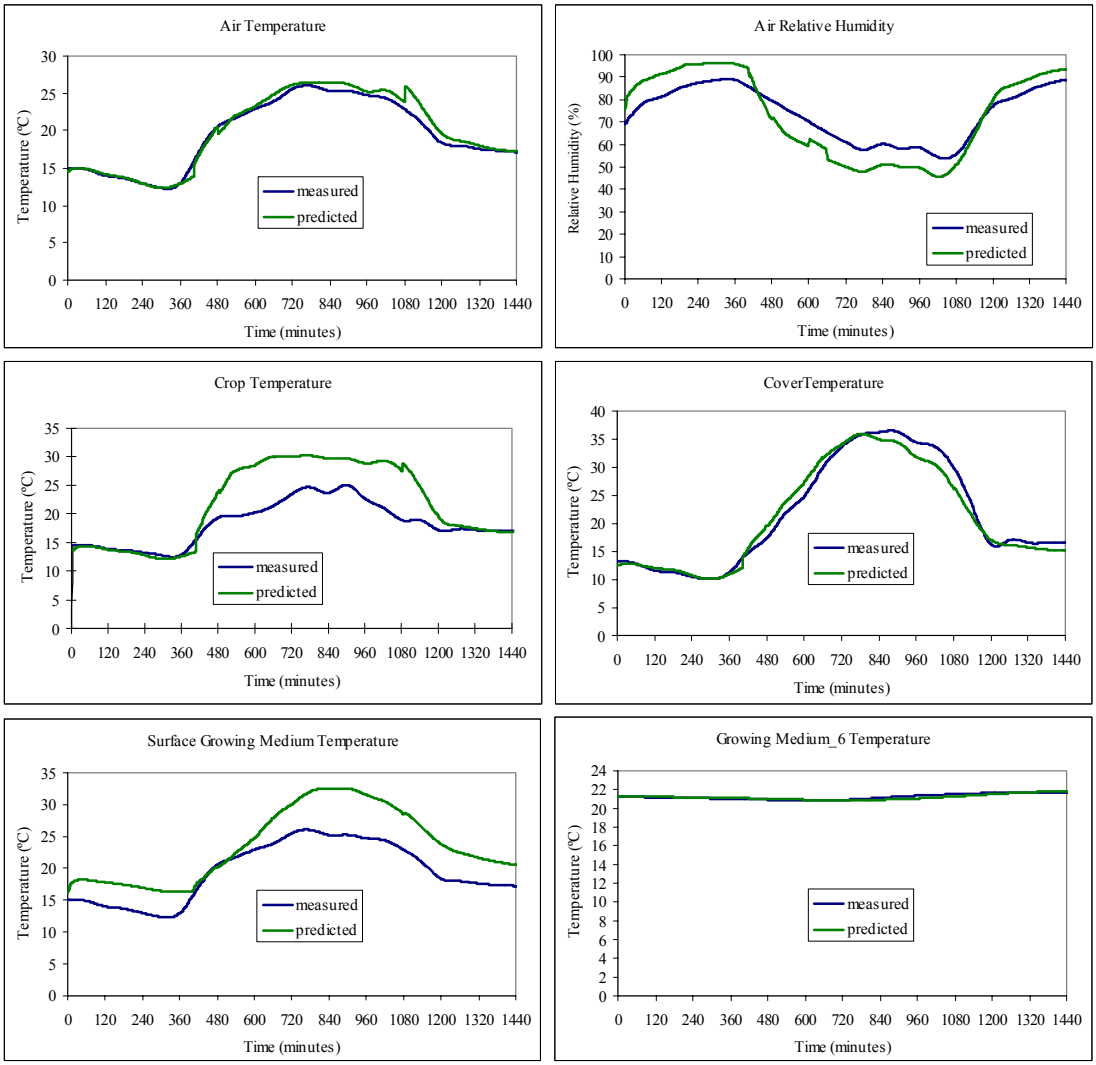



Figure 4.3 – Comparison between measured values and those predicted by the original greenhouse model for 5 June 1998

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

Results of the simulations for the relative humidity were in general not good, with errors higher than 20% mainly during the day. Of course this behaviour is directly

related with crop transpiration, evaporation from the growing medium, condensation and ventilation.

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

In conclusion, the modifications identified were mainly related with the ventilation sub-model, stomatal resistance, soil physical characteristics and convection heat transfer coefficients. However, since some inputs (soil moisture content and air speed) were calculated and not measured these could also have contributed to the global performance of the model, and this aspect should be considered in future analysis.

### 4.3.1 Crop, ventilation and soil parameters

After identifying these short comings the second phase consisted of introducing step by step changes to the model, re-running the simulation with the revised model and analysing the results. The first changes were the incorporation of (i), a stomatal resistance ($r_i$) expression developed for tomato crops which related the internal resistance to solar radiation and leaf vapour pressure deficit (Jolliet and Bailey, 1992)

$$r_i = \left[ 0.0041 \times (1 - 0.66 \times (\frac{200}{SR_i + 200}) - 0.22 VPD_{leaf}) \right]^{-1} \quad (4.33)$$

and (ii), ventilation sub-models developed by Boulard and Baille (1995) for greenhouses equipped with only side or roof openings (Eqn 3.11) and by Boulard *et al.* (1997) for greenhouses equipped with both side and roof openings (Eqn 3.12). In both cases, these sub-models express the combined effect of wind and thermal buoyancy on the air exchange rate. At this stage it was also assumed that the two sides of the leaf contribute to heat exchange by transpiration, since stomata are present on both sides of tomato leaves (Stanghellini, 1987; Boulard *et al.*, 1991).

Due to these alterations it was necessary to make some modifications to the data files needed to run the DPG programme. For example with the new ventilation sub-

model, it was necessary to incorporate information about the side and roof areas and also the vertical distance between apertures.

After this procedure, simulations were made for some days of 1998 and 2000. As mentioned before, during 2000 experiments, soil moisture content was recorded, LAI was determined over the experimental period and some soil properties were determined in the laboratory. Table 4.2 shows the *RMSE* and *ME* obtained by comparison of predicted and measured data.

Table 4.2 – Root mean square error (*RMSE*) and mean error (*ME*) between the values given by the revised model and those measured

| | | **09.05.98** | **20.05.98** | **21.06.98** | **06.07.98** | **13.05.00** |
|---|---|---|---|---|---|---|
| **$t_{ia}$ (ºC)** | *RMSE* | 1.76 | 1.45 | 0.51 | 1.21 | 1.51 |
| | *ME* | 0.53 | 0.05 | 0.39 | -0.93 | 0.10 |
| **$RH_{ia}$ (%)** | *RMSE* | 14.83 | 9.72 | 9.76 | 5.25 | 4.86 |
| | *ME* | 9.79 | 7.37 | 8.15 | -4.50 | 1.15 |
| **$t_{crop}$ (ºC)** | *RMSE* | 4.70 | 3.22 | 3.21 | 1.98 | 2.58 |
| | *ME* | 3.17 | 2.06 | 2.29 | 1.21 | 1.79 |
| **$t_{cover}$ (ºC)** | *RMSE* | 5.06 | 4.59 | 6.38 | 2.43 | 5.94 |
| | *ME* | -3.29 | -2.80 | -3.72 | -2.06 | -2.74 |
| **$t_{gm3}$ (ºC)** | *RMSE* | 2.33 | 1.63 | 2.03 | 1.44 | 7.89 |
| | *ME* | 0.65 | -1.59 | -1.89 | -1.32 | 5.69 |
| **$t_{gm5}$ (ºC)** | *RMSE* | 0.81 | 1.24 | 0.66 | 0.58 | 3.34 |
| | *ME* | -0.12 | -1.17 | -0.60 | -0.51 | 1.82 |

In general, the inside air temperature was predicted with greater accuracy than before while for most days simulation of relative humidity was worse. Crop temperature simulation improved slightly, indicating a better adaptation of the stomatal resistance sub-model than before. Cover temperature was worse than before and growing medium temperature was a little better. In fact, the results showed that the modifications did not significantly improve the simulations. It was our conviction that correction of the convection heat transfer coefficients and more adequate values of the physical properties of the soil/growing medium components (sand, clay, loam and organic matter), for the volumetric specific heat and the thermal conductivity was necessary to improve the results.

In the model, soil volumetric specific heat is determined by summing the relative contribution of the individual components and the thermal conductivity as the weighed average of the individual components, of mineral, air and water (Buchan, 1991). A brief literature review showed a wide range of values for the volumetric specific heat and thermal conductivity for the soil constituents. Since we did not

measure these parameters, simulations using different values and combinations were made to determine the most adequate for our conditions. The best results were obtained considering the thermal conductivity for sand, clay and lime equal to 0.146, 0.104 and 0.188 W $m^{-1}$ $ºC^{-1}$, respectively (Al Nakshabandi and Kohnke, 1965). The volumetric specific heat for sand, clay and lime was found to be 3.5 MJ $m^{-3}$ $ºC^{-1}$. Considering the water and organic mater volumetric specific heats, and applying the Buchan approach, it leads to values of the soil volumetric heat capacity near 3.2 MJ $m^{-3}$ $ºC^{-1}$, which is in agreement with the results of Abu-Hamdeh (2003). The organic matter thermal conductivity was assumed to be 0.25 W $m^{-1}$ $ºC^{-1}$ and the volumetric heat capacity 2.5 MJ $m^{-3}$ $ºC^{-1}$ (Buchan, 1991).

Maximum and minimum limits for the stomatal resistance were also modified considering the appropriate values for a tomato crop (200 and 3500 s $m^{-1}$) (Chalabi and Bailey, 1989; Papadakis *et al*., 1994) and the percentage of growing medium area exposed to direct solar radiation was readjusted for a larger crop.

### 4.3.2 Convection heat transfer coefficients

Convection heat transfer ($Q_c$), is proportional to the temperature difference between the surface and the air ($\Delta t$), as described by Newton's law. The proportionality is achieved by the convection heat transfer coefficient ($h_c$).

$$Q_c = h_c \Delta t \tag{4.34}$$

Determination of convection heat transfer coefficients is complex mainly due to the high quantity of influencing factors, as the surface shape, position and the nature of the involved heat flows (Bailey and Meneses, 1995). Convection analysis can be simplified by using non dimensional groups as the Grashof (Gr), Reynolds (Re), Prandtl (Pr) and Nusselt (Nu) numbers.

$$\mathrm{Pr} = \frac{\upsilon}{\kappa} \tag{4.35}$$

$$Gr = \frac{\beta l^3 g \Delta t}{\upsilon^2} \tag{4.36}$$

$$\mathrm{Re} = \frac{vl}{\upsilon} \tag{4.37}$$

where $\upsilon$ is the kinematic viscosity of air, $\kappa$ the thermal diffusivity of air, $\beta$ the thermal expansion coefficient of air, l the characteristic dimension of the surface, g the

acceleration of gravity and *v* the air speed. In the case of air the Prandtl number can be taken as constant, equal to 0.71, since for gases it is practically independent of temperature and pressure.

The convection heat transfer coefficient is a function of the nature of convection (free, forced or mixed) and the type of flow (laminar or turbulent). It is determined by the Nusselt number (*Nu*), where k is the air thermal conductivity.

$$h_c = \frac{kNu}{l} \tag{4.38}$$

The Nusselt number is a function of the Grashof and Prandtl numbers if convection is free or natural and of the Reynolds and Prandtl if it is forced (Monteith, 1973).

$$Nu_n = b_1 (Gr\,\mathrm{Pr})^n \tag{4.39}$$

$$Nu_f = b_2\,\mathrm{Re}^p\,\mathrm{Pr}^m \tag{4.40}$$

where $b_1$, $b_2$, *m*, *n* and *p* are constants which depend of the surface geometry and nature of the flux. However, in greenhouses most of the convection heat exchange is due to mixed convection with both processes involved (Papadakis *et al.*, 1992; Stanghellini, 1987). In this case Stanghellini (1987, 1993) suggested that $Nu_m$ was a function of the Gr and Re numbers.

$$Nu_m = b_3 (Gr + Gr')^n \tag{4.41}$$

To determine $h_c$ it is necessary to establish some criteria which allow the identification of the nature of convection and the type of flux. Comparison between Gr and Re numbers enables a decision on which force is responsible for the heat exchange. If Gr is high and Re low, convective transfer is due to a thermal gradient and the convection is free. On the contrary, if Re is high and Gr low, transfer is due to other causes and forced convection is predominant. Monteith (1973), Bot and van de Braak (1995) and Roy *et al*. (2002) suggested some relations between Gr and Re which identify the conditions for each of the processes: if $Gr > 16\,Re^2$ convection is free and if $Re^2 > 10\,Gr$ it is forced. Especially for the cover Papadakis (1992) suggested other criteria: if $Gr/Re^{5/3} > 200$ convection is free and if $Re^{2.4}/Gr > 7000$ it is forced. Differentiation between laminar and turbulent flux is based on the magnitude of the Gr number in the case of free convection ($Gr < 10^8$ laminar, $Gr \geq 10^8$ turbulent) and Re for forced convection ($Re < 10^5$ laminar, $Re \geq 10^5$ turbulent) (Monteith, 1973; Roy *et al*., 2002).

Convection heat transfer coefficients can be obtained through the fitting of experimental data to climate models (Seginer *et al*., 1988), the main disadvantage being the loss of the physical dimension of the transfer process (Navas, 1996). Other approaches are based on energy balances (Bailey and Meneses, 1995) or in sophisticated calibration processes with simulation programmes (Vollebreght and van de Braak, 1995).

It is frequent to find in the literature expressions for the convection heat transfer coefficients obtained by fitting data with climate models. Most of these cases do not take in account the physical nature of the processes. Convection heat transfer coefficients were determined, by analysing experimental data considering the nature of the convection and the type of flux, using non dimensional numbers, such as those of Reynolds, Grashof, Nusselt and Prandtl (Baptista and Meneses,2005).

It does not exist a general equation for the convection heat transfer coefficients that applies to all greenhouses, because of the specific conditions, the surface nature or position, climatic conditions or nature and type of flow. This method provides a methodical analysis to obtain the relevant expressions.

As mentioned before, the experiments were carried out in plastic greenhouses with a tomato crop located at Lisbon and the data used for this analysis were recorded between February and July 2000. Depending on the component studied, the convection heat transfer coefficient ($h_c$) was related to temperature difference ($\Delta t$), wind speed ($v_w$) or inside air speed ($v_{ia}$).

#### 4.3.2.1 Methodology

The expressions for the convection heat transfer coefficients were obtained by using a methodology which allowed a study of the nature of the convection and the type of flow as a function of the specific greenhouse characteristics and environmental conditions:

1. Selection of characteristic days, these were characterised by different conditions of air temperature, wind speed, solar radiation, inside air speed and ventilation management. For each of the greenhouse components representative days were selected (Table 4.3).

Concerning the convection heat transfer between the cover and the outside air, the most important factor is the wind speed, which usually causes forced convection.

However, this effect can be less evident if the temperature difference is high, which happens when solar radiation is high. The days chosen to include different combinations of wind and radiation were 26 and 29 April, 7 June and 18 July.

Table 4.3 – Characteristics of selected days to determine the various convection heat transfer coefficients

| Day | Solar Radiation ($W\ m^{-2}$) | | Wind Speed ($m\ s^{-1}$) | | Inside Air Speed ($m\ s^{-1}$) | | Ventilation | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Night | | Day |
| | Max | Mean | Max | Mean | Max | Mean | CV | PV | |
| 20/4/00 | 382 | 76 | 3.3 | 1.7 | 0.15 | 0.08 | no | yes | yes |
| 26/4/00 | 1070 | 306 | 2.2 | 0.7 | 0.12 | 0.05 | no | yes | yes |
| 29/4/00 | 173 | 46 | 4.7 | 2.1 | 0.20 | 0.10 | no | yes | yes |
| 22/5/00 | 1000 | 350 | 2.0 | 0.8 | 0.11 | 0.05 | no | yes | yes |
| 25/5/00 | 495 | 132 | 1.0 | 0.5 | 0.08 | 0.05 | no | yes | yes |
| 7/6/00 | 1000 | 363 | 1.6 | 0.9 | 0.11 | 0.09 | yes | | yes |
| 15/7/00 | 990 | 350 | 2.0 | 1.1 | 0.13 | 0.10 | yes | | yes |
| 18/7/00 | 680 | 191 | 2.0 | 0.7 | 0.13 | 0.09 | yes | | yes |
| 23/7/00 | 960 | 260 | 2.7 | 1.0 | 0.15 | 0.10 | yes | | yes |

In relation to the internal components, usually the most relevant factor is greenhouse ventilation, because of the influence on inside air speed. To determine the convection heat transfer coefficients between the inside air and the cover and between the growing medium/soil and the inside air the days analysed were 29 April, 25 May, 15 and 23 July. During April and May the vents were closed during the night period (CV greenhouse) while in July, they were open. For the crop, the nature of the convective process is also influenced by the crop characteristics, such as leaf size and plant height. The selected days were 20 and 26 April, 22 and 25 May, 7 June and 18 July, covering different conditions of ventilation management and crop development. Again, different combinations of wind and solar radiation characteristics were included. All calculations were by using hourly data for each chosen day;

2. Calculate the Grashof and Reynolds numbers as a way to identify free (natural), forced or mixed convection, by using established comparison criteria. It was considered air kinematic viscosity between 14.5 and $15.9 \times 10^{-6}$ $m^2\ s^{-1}$ and thermal expansion coefficient between 0.0033 and 0.0035 $K^{-1}$;

3. Determine the type of flux, laminar or turbulent, depending on the sizes of Gr and Re for free or forced convection, respectively;

4. Calculate the Nusselt number using some expressions obtained experimentally as a function of Gr & Pr or Re & Pr depending on whether the convection was free or forced and the type of flux. When the convection was predominantly mixed the expression presented by Stanghellini was used;

5. Calculate $h_c$, using Eqn 4.38, where $k$ is the thermal conductivity of air and $l$ the characteristic dimension for the relevant component (cover – 7.4 m, soil - 14 m, growing medium - 11.6 m). For the heat transfer between crop and air, two characteristic dimensions were tested, 0.05 and 0.1 m, based on previous work (Roy *et al.*, 2002; Bailey, 2003). Both values were tested in the model to identify the most appropriate;

6. Obtain $h_c$ final expressions. Depending on the analysed component, $h_c$ was related with temperature difference, wind speed and inside air speed. Expressions were obtained by linear regression or by adjusting tendency lines, using statistics programmes (TableCurve 2D and 3D) which allowed equations to be fitted to the data: $h_{c,\ co\rightarrow oa} = f(\Delta t,\ v_w)$, $h_{c,\ ia\rightarrow co} = f(\Delta t)$, $h_{c,\ s\rightarrow ia} = f(\Delta t)$, $h_{c,\ gm\rightarrow ia} = f(\Delta t)$, $h_{c,\ cr\rightarrow ia} = f(\Delta t,\ v_{ia})$.

#### 4.3.2.2 Results

Cover → Outside air

To determine the predominant nature of convection, the relation between wind speed and temperature difference was graphically represented for the selected days (Figure 4.4). The transition curves between free, mixed and forced convection were obtained by resolution of the Grashof and Reynolds numbers for pure free or forced convection conditions, according to the criteria proposed by Papadakis *et al*. (1992) for the cover component (if $Gr/Re^{5/3} > 200$ convection is free and if $Re^{2.4}/Gr > 7000$ it is forced). Table 4.4 provides the transition equations obtained.

Table 4.4 – Transition equations obtained for the external surface of the greenhouse cover

| Day | Free – Mixed | Forced - Mixed |
|---|---|---|
| 26/4/00 | $v_w = 0.158\lvert\Delta t\rvert^{0.6}$ | $v_w = 2.182\lvert\Delta t\rvert^{0.42}$ |
| 29/4/00 | $v_w = 0.158\lvert\Delta t\rvert^{0.6}$ | $v_w = 2.181\lvert\Delta t\rvert^{0.42}$ |
| 7/6/00 | $v_w = 0.150\lvert\Delta t\rvert^{0.6}$ | $v_w = 2.156\lvert\Delta t\rvert^{0.42}$ |
| 18/7/00 | $v_w = 0.154\lvert\Delta t\rvert^{0.6}$ | $v_w = 2.168\lvert\Delta t\rvert^{0.42}$ |

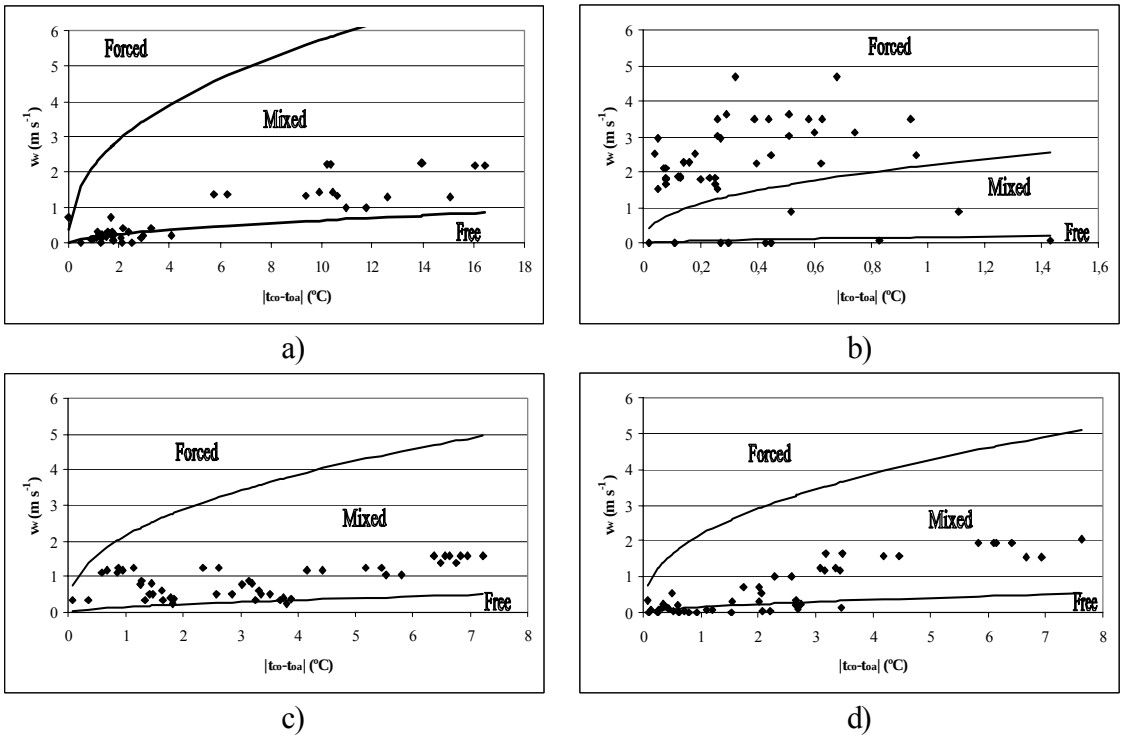



Figure 4.4 – Determination of predominant type of convection between the cover and outside air. a) 26 April, b) 29 April, c) 7 June and d) 18 July 2000.

Analysing the figure above we can observe that convection between the cover and the outside air was predominantly mixed, which is agreement with Kittas (1986), Papadakis *et al.* (1992) and Navas (1996). Only exceptionally the convection was free corresponding to periods when the wind speed was lower than 0.5 m s$^{-1}$. The 29 April data clearly showed the condition of forced convection, explained by the low temperature difference (< 1.5 ºC) and relatively high wind speed (> 1 m s$^{-1}$). Also, it is possible to observe that even with a high temperature difference; of about 15 ºC, convection was still mixed and not free, due to the wind speed being higher than 1 m s$^{-1}$, and influencing convection heat exchange. The flux was mainly turbulent ($Gr \geq 10^8$ and $Re \geq 10^5$).

The Nusselt number was determined for mixed convection and turbulent flux following the Stanghellini (1987) methodology, considering the expressions given by Papadakis *et al*. (1992) for pure free and forced convection in the turbulent regime:

$$Nu_n = 0.19(Gr\,\mathrm{Pr})^{0.33}$$

$$Nu_f = 0.033\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.33}$$

$$Nu_m = 0.19(Gr + 5\times10^{-3}\,\mathrm{Re}^{2.42})^{0.33}$$

Values of $h_{c,co\to oa}$, were determined and related with temperature difference and wind speed. Several models were obtained, we selected the parsimonious model presented below, which was the simplest with the greatest explanatory power (n = 192, $r_a^2 = 0.99$, $RMSE = 0.379$).

$$h_{c,co\to oa} = 2.020 + 0.084\left|t_{co} - t_{oa}\right| + 2.985 v_w \tag{4.42}$$

This expression results from a systematic analysis of experimental data and corresponds to the expression that will be introduced in the climate model to describe the convection heat transfer coefficient between the cover and outside air.

Inside air → Cover

For the selected days, the maximum inside air speed was 0.2 m $s^{-1}$, even with the vents opened. The transition equations shown in Table 4.5 were obtained using the criteria mentioned before and Figure 4.5 shows the nature of the convection.

Table 4.5 – Transition equations obtained for the internal surface of the greenhouse cover

| Day | Free – Mixed | Forced - Mixed |
|---|---|---|
| 29/4/00 | $v_{ia} = 0.158\left\|\Delta t\right\|^{0.6}$ | $v_{ia} = 2.182\left\|\Delta t\right\|^{0.42}$ |
| 25/5/00 | $v_{ia} = 0.154\left\|\Delta t\right\|^{0.6}$ | $v_{ia} = 2.170\left\|\Delta t\right\|^{0.42}$ |
| 15/7/00 | $v_{ia} = 0.149\left\|\Delta t\right\|^{0.6}$ | $v_{ia} = 2.167\left\|\Delta t\right\|^{0.42}$ |
| 23/7/00 | $v_{ia} = 0.154\left\|\Delta t\right\|^{0.6}$ | $v_{ia} = 2.175\left\|\Delta t\right\|^{0.42}$ |

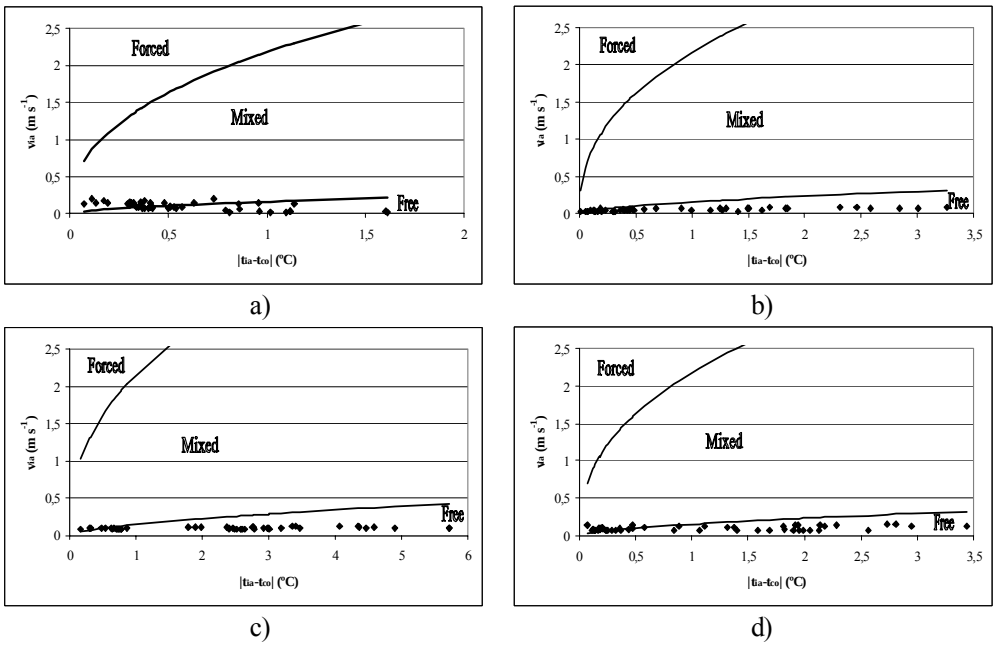



Figure 4.5 – Determination of predominant type of convection between the inside air and cover. a) 29 April, b) 25 May, c) 15 July and d) 23 July 2000.

Analysis of Figure 4.5 shows that the convection was predominantly free. Only sporadically when the temperature difference was almost zero and some air movement occurred was the convection mixed. The flux was always turbulent (Gr ≥ $10^8$). The Nusselt number was calculated using the expression presented by Bot and van de Braak (1995), for free convection in the turbulent regime.

$$Nu = 0.13(Gr\,\mathrm{Pr})^{0.33}$$

The determination of $h_{c,\ ia\rightarrow co}$ was by the same procedure used before and then related with temperature difference, since, as expected the inside air speed, did not have a significant effect, due to the free nature of the convection. The best model introduced in the climate model to describe the convection heat transfer coefficient between the inside air and the cover, is given in Eqn 4.43 and shown in Figure 4.6. It was based on 192 data values and had values of $r_a^2 = 0.99$ and $RMSE = 0.022$.

$$h_{c,ia\rightarrow co} = 1.470\left|t_{ia} - t_{co}\right|^{0.32} \tag{4.43}$$

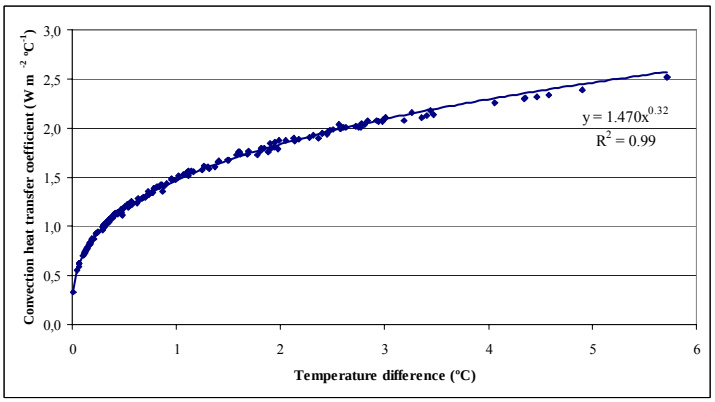



Figure 4.6 – Convection heat transfer coefficient between the inside air and the greenhouse cover *versus* temperature difference and the adjusted tendency line

Soil → Inside air and Growing medium → Inside air

Convection heat transfers between soil/growing medium and inside air were studied assuming the convection was free if Gr > 16 $Re^2$ and forced if $Re^2$ > 10 Gr. Table 4.6 shows the transition equations obtained.

Table 4.6 - Transition equations obtained for convection from the soil and growing medium

| Day | SOIL | | GROWING MEDIUM | |
|---|---|---|---|---|
| | **Free – Mixed** | **Forced - Mixed** | **Free – Mixed** | **Forced - Mixed** |
| 29/4/00 | $v_{ia} = 0.173\|\Delta t\|^{0.5}$ | $v_{ia} = 2.192\|\Delta t\|^{0.5}$ | $v_{ia} = 0.158\|\Delta t\|^{0.5}$ | $v_{ia} = 1.996\|\Delta t\|^{0.5}$ |
| 25/5/00 | $v_{ia} = 0.171\|\Delta t\|^{0.5}$ | $v_{ia} = 2.161\|\Delta t\|^{0.5}$ | $v_{ia} = 0.156\|\Delta t\|^{0.5}$ | $v_{ia} = 1.967\|\Delta t\|^{0.5}$ |
| 15/7/00 | $v_{ia} = 0.168\|\Delta t\|^{0.5}$ | $v_{ia} = 2.129\|\Delta t\|^{0.5}$ | $v_{ia} = 0.153\|\Delta t\|^{0.5}$ | $v_{ia} = 1.938\|\Delta t\|^{0.5}$ |
| 23/7/00 | $v_{ia} = 0.171\|\Delta t\|^{0.5}$ | $v_{ia} = 2.161\|\Delta t\|^{0.5}$ | $v_{ia} = 0.156\|\Delta t\|^{0.5}$ | $v_{ia} = 1.967\|\Delta t\|^{0.5}$ |

In the Figures 4.7 and 4.8 are shown the relations between inside air speed and temperature difference between the soil and air, and the growing medium and air, respectively.

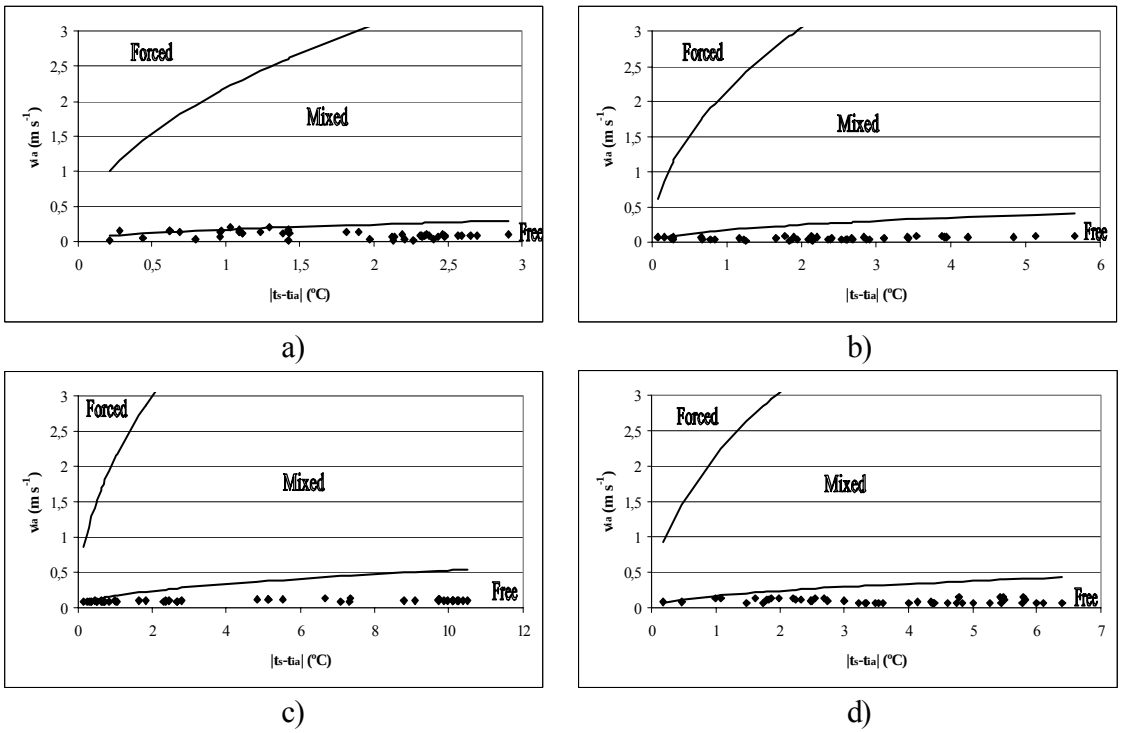



Figure 4.7 – Determination of predominant type of convection between the soil and inside air. a) 29 April, b) 25 May, c) 15 July and d) 23 July 2000.

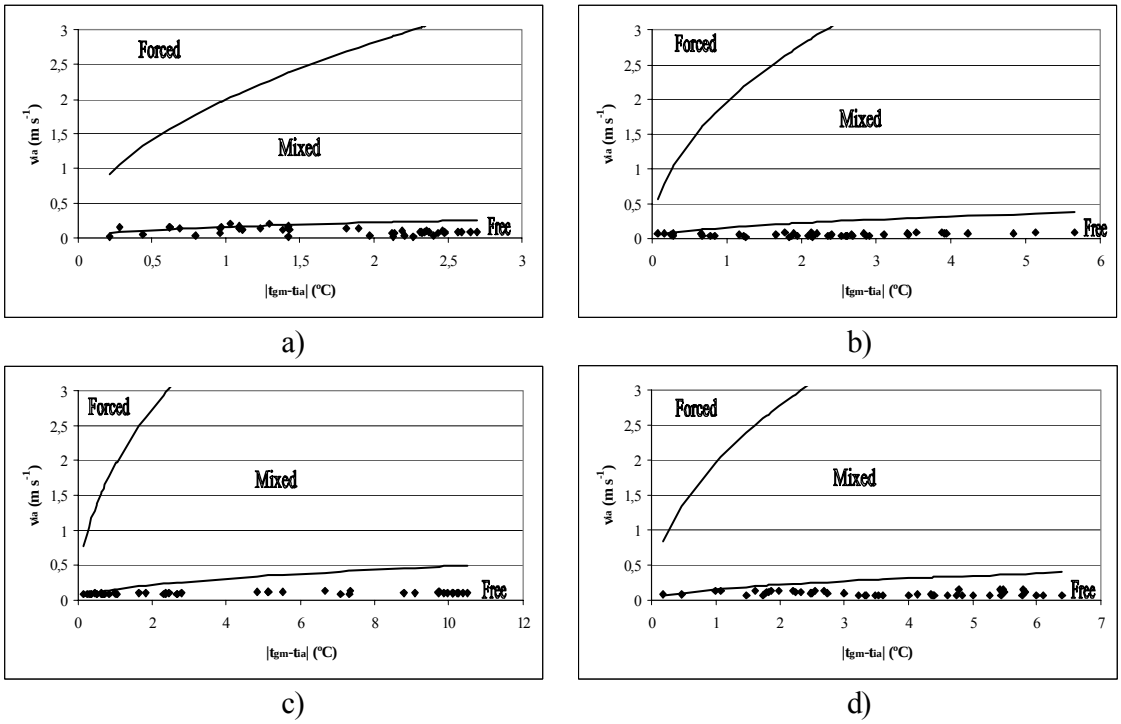



Figure 4.8 – Determination of predominant type of convection between the growing medium and inside air. a) 29 April, b) 25 May, c) 15 July and d) 23 July 2000.

In both cases convection is predominantly free and the flux turbulent (Gr ≥ $10^8$). The Nusselt number was calculated using the expression mentioned before for free convection in the turbulent regime. The determination of $h_{c,\ s\rightarrow ia}$ and $h_{c,\ gm\rightarrow ia}$ followed the same methodology and were related with the respective temperature difference. The best models, Eqns 4.44 and 4.45, shown in Figures 4.9 and 4.10, for which $r_a^2$ = 0.99 and *RMSE* = 0.022 and 0.017 were obtained with a set of 192 data values.

$$h_{c,s\rightarrow ia} = 1.464\left|t_s - t_{ia}\right|^{0.32} \tag{4.44}$$

$$h_{c,gm\rightarrow ia} = 1.215\left|t_{gm} - t_{ia}\right|^{0.32} \tag{4.45}$$

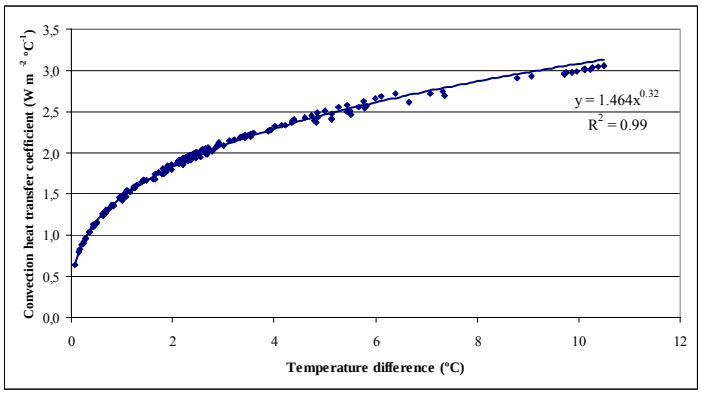



Figure 4.9 - Soil → inside air convection heat transfer coefficient *versus* temperature difference and the adjusted tendency line

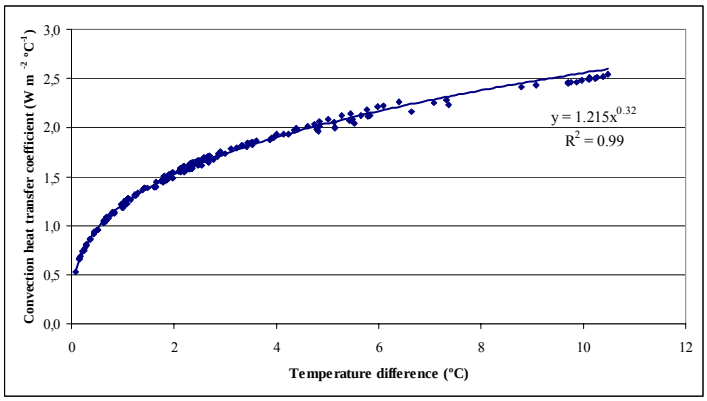



Figure 4.10 – Growing medium → inside air convection heat transfer coefficient *versus* temperature difference and the adjusted tendency line

Crop → Inside air

It is important to mention that the convection heat transfer coefficient in this case refers to the leaves and not to the crop, since the leaves are the element that exchange heat with surroundings. Leaves are considered as plane surfaces, rectangular and horizontal (Stanghellini, 1995). To obtain the convection heat transfer between the crop and the air, the expression obtained should be multiplied by 2LAI, since both sides of the leaves contribute to the convection heat exchange. As mentioned before convection between the leaves and the air was studied considering two characteristic dimensions, 0.05 and 0.1m.

Figures 4.11 and 4.12 present the results obtained for both cases and allow identification of the nature of the process. The transition equations are shown in Table 4.7.

Table 4.7 – Transition equations obtained for the two leaf characteristic dimensions

| l (m) | Free – Mixed | Forced - Mixed |
|---|---|---|
| 0.05 | $v_{ia} = 0.010\|\Delta t\|^{0.5}$ | $v_{ia} = 0.131\|\Delta t\|^{0.5}$ |
| 0.1 | $v_{ia} = 0.015\|\Delta t\|^{0.5}$ | $v_{ia} = 0.185\|\Delta t\|^{0.5}$ |

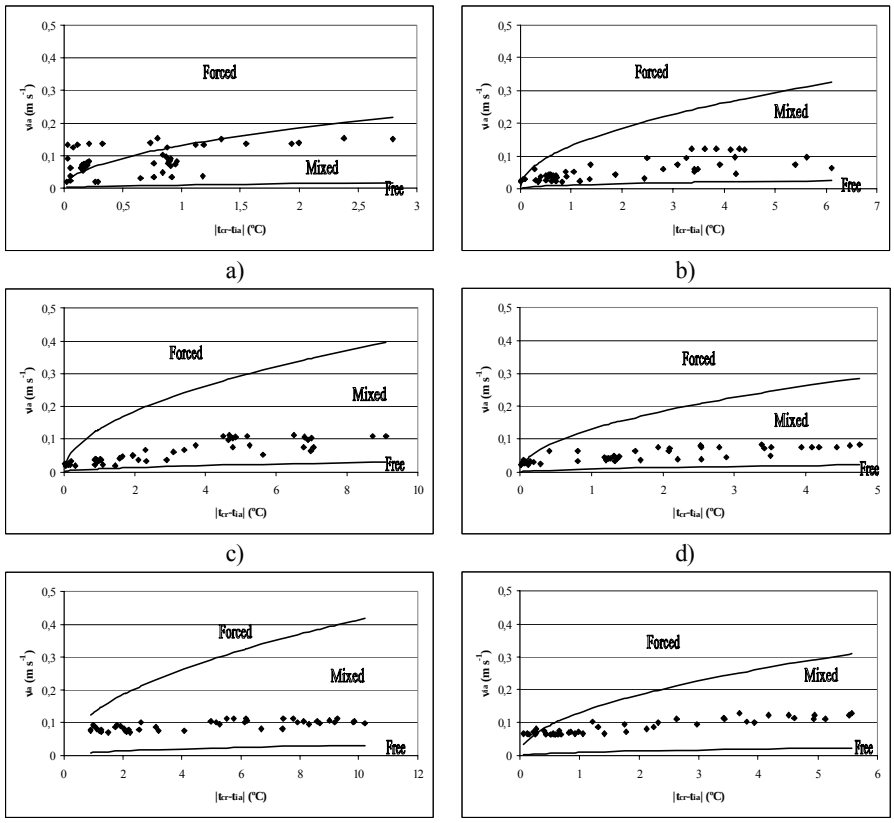



Figure 4.11 – Determination of predominant type of convection between the leaves (l=0.05m) and inside air. a) 20 April, b) 26 April, c) 22 May, d) 25 May, e) 7 June and f) 18 July 2000.

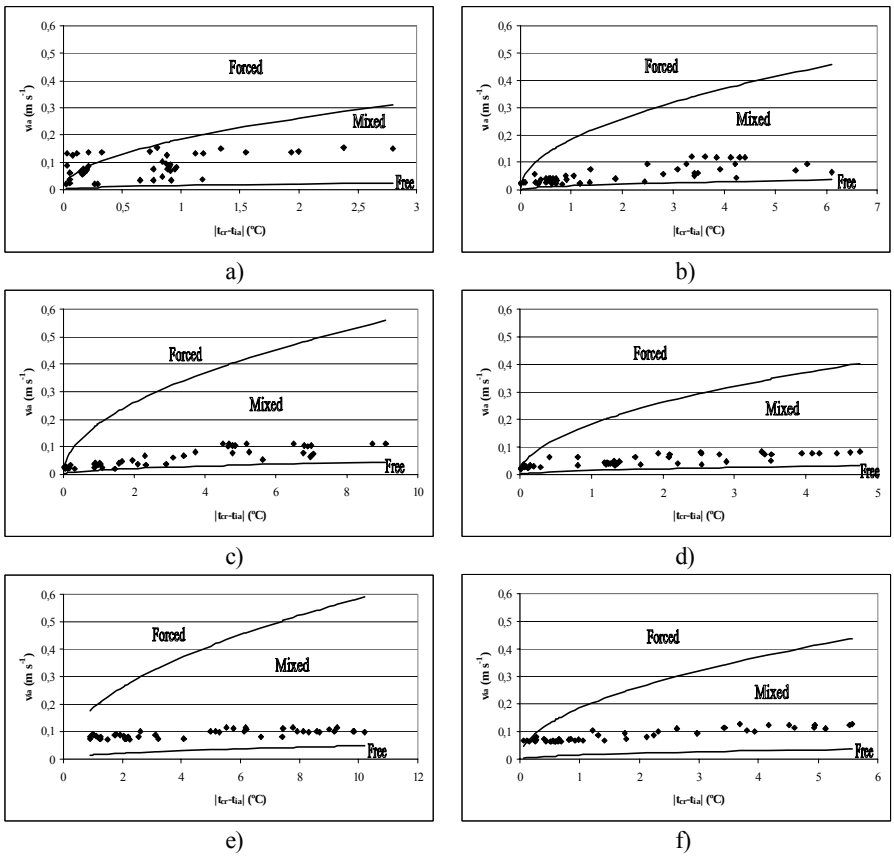



Figure 4.12 – Determination of predominant type of convection between the leaves (l=0.1m) and inside air. a) 20 April, b) 26 April, c) 22 May, d) 25 May, e) 7 June and f) 18 July 2000.

A complementary analysis of the leaf/crop and air temperature difference showed that crop temperature was, during almost all of the experimental work, lower than the air temperature during the day period while during the night, the crop and air temperatures were very similar. Due to this behaviour, it was expected that during the day free convection occurs and during the night it was forced or mixed, depending on the air speed.

However, observation of the Figures 4.11 and 4.12 shows for all days and for both leaf dimensions, that convection was never free and rarely forced. Most of the time convection was mixed and a function of two factors, temperature difference and air speed. Even a temperature difference of 10 ºC the convection was still mixed, since in the leaf surroundings some air movement always occurs. Exceptionally, when simultaneously the air speed was higher than 0.1 m $s^{-1}$ and the temperature difference lower than 0.5 ºC, did we found forced convection, as mentioned before by Stanghellini (1987) and Bailey and Meneses (1995).

The flux was found to be laminar ($Gr < 10^8$ and $Re < 10^5$). The expression used to calculate Nusselt number was that proposed by Stanghellini (1987), for mixed convection and laminar flux;

$$Nu_m = 0.37\left(Gr + 6.92\,\mathrm{Re}^2\right)^{0.25}$$

The heat transfer coefficient was determined for the two characteristic dimensions. Again the parsimonious models were selected. Both were tested in the climate model, and as Eqn 4.46 fitted the data better, it was used in the final model.

Table 4.8 – Convection heat transfer coefficients for tomato leaves

| **l (m)** | $h_{c,\ cr\rightarrow ia}$ (W $m^{-2}$ ºC$^{-1}$) | **n** | $r_a^2$ | ***RMSE*** | |
|---|---|---|---|---|---|
| 0.05 | $h_{c,cr\rightarrow ia} = 2.349 + 0.046\left\|t_{cr} - t_{ia}\right\| + 32.703 v_{ia}$ | 288 | 0.98 | 0.141 | (4.46) |
| 0.1 | $h_{c,cr\rightarrow ia} = 3.492 + 0.111\left\|t_{cr} - t_{ia}\right\| + 44.488 v_{ia}$ | 288 | 0.98 | 0.063 | (4.47) |

## 4.4 Final climate model

The final climate model includes new sub-models for ventilation, stomatal resistance and the convection heat transfer coefficients. The development of the first two was described in Section 4.3.1 and the third in Section 4.3.2. Some parameters

related with the soil thermal characteristics were also modified, as mentioned in Section 4.3.1.

The new model was considered adequate when used with the specific conditions of weather, crop and greenhouses used in our experiments. The main structure of the model was maintained. Air properties such as density ($\rho$), enthalpy ($i$), absolute humidity ($w$), vapour pressure at saturation ($e^*$), dew point temperature ($t_d$), psychrometric constant ($\gamma$), latent heat of vaporization ($\lambda$), thermal conductivity ($k_{ia}$), specific heat ($c_{ia}$), kinematic viscosity ($\upsilon$) and the water specific heat ($c_{wa}$) and thermal conductivity ($k_{wa}$) are calculated in the model as a function of the temperature. As explained, the soil volumetric specific heat and thermal conductivity are also determined in the model as a function of the volumetric specific heat and thermal conductivity of each of the soil components (sand, loam, clay, organic matter, air and water). The sky temperature is determined as a function of the outside air dry bulb and dew point temperatures. The aerodynamic resistance of tomato leaves ($r_e$) is calculated as a function of the inside air density, specific heat and the crop to air convection heat transfer coefficient. A full description was given by (Navas, 1996).

### 4.4.1 Validation of the model

Validation is a very important step in modelling processes since it tests the model performance. In this thesis validation was achieved by comparison of experimental and predicted data for some days of 1998 and 2000. These data were used only for validation and never to adjust parameters of the model.

#### 4.4.1.1 Experimental data and parameters of the model

Data used to validate the climate model were recorded each minute, between 12 and 15 May and 15 and 18 June in 2000. During 1998, data were recorded on an hourly basis and to provide values at 1 minute intervals an interpolation in time was undertaken using the cubic spline method (Stoer and Bulirsch, 1980). Data recorded on 29 April, 5 June and 6 July was used to cover all experimental conditions.

Constants relating to the optical properties of the greenhouse, crop, growing medium and soil are presented in Table 4.9. Growing medium/soil emissivity ($\varepsilon$) and

reflectivities (φ) were determined as a function of the moisture content ($x_{wa}$) (Horton, 1989):

$$\varepsilon = 0.90 + 0.18 x_{wa} \tag{4.48}$$

$$\varphi_{SR} = \begin{cases} 0.25 & if \quad x_{wa} < 0.10 \\ 0.35 - x_{wa} & if \quad 0.10 \leq x_{wa} \leq 0.25 \\ 0.10 & if \quad x_{wa} > 0.25 \end{cases} \tag{4.49}$$

Table 4.9 – Optical properties of the growing medium, soil, crop and cover for the days used in the validation process

| Date | | 1998 | | | 2000 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **29/4** | **5/6** | **6/7** | **12/5** | **13/5** | **14/5** | **15/5** | **15/6** | **16/6** | **17/6** | **18/6** |
| **Day number** | | 119 | 156 | 187 | 132 | 133 | 134 | 135 | 166 | 167 | 168 | 169 |
| **Growing medium** | | | | | | | | | | | | |
| | Emissivity, % | 0.96 | 0.95 | 0.96 | 0.97 | 0.97 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 |
| | Absorptivity, % | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 |
| | Reflectivity, % | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| **Soil** | | | | | | | | | | | | |
| | Emissivity, % | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 |
| | Absorptivity, % | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 |
| | Reflectivity, % | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| **Crop** | | | | | | | | | | | | |
| | LAI | 2.4 | 4.0 | 3.6 | 4.8 | 4.8 | 4.8 | 4.8 | 4.4 | 4.4 | 4.4 | 4.4 |
| | Emissivity, % | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 |
| | Absorptivity, % | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| **Cover material** | | | | | | | | | | | | |
| Thermal radiation | Emissivity, % | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 |
| | Reflectivity, % | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| | Transmissivity,% | 0.37 | 0.37 | 0.37 | 0.37 | 0.37 | 0.37 | 0.37 | 0.37 | 0.37 | 0.37 | 0.37 |
| Solar radiation | Absorptivity, % | 0.15 | 0.15 | 0.15 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 |
| | Reflectivity, % | 0.14 | 0.14 | 0.14 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 | 0.16 |
| | Transmissivity,% | 0.71 | 0.71 | 0.71 | 0.68 | 0.68 | 0.68 | 0.68 | 0.68 | 0.68 | 0.68 | 0.68 |

Table 4.10 – General characteristics of the greenhouse

| | Greenhouse | Growing medium | | | Latitude | 38º42' N |
|---|---|---|---|---|---|---|
| | | | | | Longitude | 9º11'W |
| Area, $m^2$ | 182 | 74.2 | | | Altitude, m | 50 |
| | Layer1 | Layer2 | Layer3 | Layer4 | Layer5 | Layer6 |
| Soil thickness, m | 0.002 | 0.02 | 0.056 | 0.070 | 0.104 | 0.248 |

#### 4.4.1.2 Results and discussion

Since data recorded on several days were used to validate the climate model, we decide to present the results for one day in each of the selected periods (1998, May 2000 and June 2000). The statistical parameters presented are the mean error (*ME*), the root

mean square error (*RMSE*) and the adjusted determination coefficient ($r_a^2$) for all the days.

#### 4.4.1.2.1 Validation with 1998 data

Table 4.11 shows the statistical parameters obtained by analysing the measured and predicted data for the three days in 1998.

Table 4.11 – Simulation statistics for predictions during the validation days of 1998

| | **29-April-98** | | | **5-June-98** | | | **6-July-98** | | |
|---|---|---|---|---|---|---|---|---|---|
| | ***ME*** | ***RMSE*** | $r_a^2$ | ***ME*** | ***RMSE*** | $r_a^2$ | ***ME*** | ***RMSE*** | $r_a^2$ |
| **$t_{ia}$ (ºC)** | -0,93 | 2,31 | 0,93 | -1,02 | 1,60 | 0,99 | -0,32 | 0,81 | 0,99 |
| **$RH_{ia}$ (%)** | -2,82 | 4,45 | 0,87 | -2,36 | 4,97 | 0,96 | -3,25 | 4,01 | 0,92 |
| **$t_{cr}$ (ºC)** | -1,36 | 2,06 | 0,94 | -0,81 | 1,31 | 0,93 | 0,99 | 1,88 | 0,94 |
| **$t_{co}$ (ºC)** | -0,19 | 1,65 | 0,95 | -1,64 | 2,84 | 0,95 | -1,66 | 1,78 | 0,99 |
| **$t_{gm3}$ (ºC)** | -0,45 | 0,51 | 0,93 | -1,08 | 1,41 | 0,87 | -0,44 | 0,48 | 0,92 |
| **$t_{gm5}$ (ºC)** | -0,06 | 0,38 | 0,24 | -0,06 | 0,68 | 0,39 | 0,68 | 0,74 | 0,48 |
| **$t_{gm6}$ (ºC)** | 0,12 | 0,18 | 0,21 | -0,02 | 0,27 | 0,00 | 0,28 | 0,30 | 0,38 |
| **$t_{s3}$ (ºC)** | -0,99 | 1,10 | 0,64 | -1,24 | 1,51 | 0,79 | -0,83 | 0,88 | 0,89 |
| **$t_{s5}$ (ºC)** | -0,05 | 0,39 | 0,32 | -0,05 | 0,68 | 0,43 | 0,69 | 0,75 | 0,44 |
| **$t_{s6}$ (ºC)** | 0,13 | 0,18 | 0,21 | -0,02 | 0,27 | 0,00 | 0,28 | 0,30 | 0,34 |

A general analysis of this Table shows that good agreement between the simulated and measured results was obtained. For the air temperature a maximum *RMSE* of 2.3ºC was found with the mean error between -1 and -0.3 ºC, being the predicted values consistently lower than those obtained experimentally. Also, the relative humidity was simulated with good accuracy, presenting a maximum *RMSE* around 5%, and mean error between -3.3 and -2.4%, which is good considering that humidity, is one of the more difficult parameters to estimate. Simulation of crop temperature also presented satisfactory results with a maximum *RMSE* of 2.1ºC. Measured cover temperature was higher than predicted, but again the maximum *RMSE* of 2.8ºC showed good agreement. Concerning the growing medium and soil temperatures at different depths, results were very good. During the 1998 experiments growing medium temperature was measured only at 5, 20 and 50 cm depths, and we can see that agreement of the simulated and measured data is almost perfect, which confirms the correct adjustment of soil properties.

An aspect of particular importance is the different ventilation managements used on these days (see Table 3.12), and the results seem to not be influenced by this, which

indirectly confirms the correct choice of the ventilation sub-model. Figure 4.13 shows the performance of the model for 6 July; giving a comparison of the measured and predicted data over the 24 hours for some of the process variables.


Figure 4.13 – Results of the simulation for 6 July 1998 for the PV greenhouse

Analysis of the above figure shows good performance of the model over the simulation period and allows the observation of some differences during the night and day periods. Except for the cover temperature, all the others present good agreement during the night, with the maximum differences occurring during the day. The dominant

factors in the day energy balance are solar radiation, the transmissivity of the cover material and plant transpiration. In fact, this last factor is very important in determining the crop temperature. Two things could happen, the first is an incorrect sensor reading and the other is that transpiration was under estimated by the model, which could be related with the LAI. However, the results are coherent, since the predicted air relative humidity is lower than the measured value for most of the day period. The predicted cover temperature is consistently lower than measured, but with a good performance, since the lines have the same variation over the day, which explains the high determination coefficient ($r_a^2$ = 0.99). Again, this can be explained by a systematic reading error or due to errors in the simulation of the cover heat balance. Analysing the behaviour of the other greenhouse components it seems that a reading error is the more realistic explanation. In fact, during the night, the cover heat balance is affected mainly by the sky temperature and the convection heat transfer coefficient. The sky temperature seems to be adequate, which is shown by the good agreement found for the rest of the components, and the convection heat transfer was determined for this specific greenhouse and conditions.

For the measured and predicted growing medium temperatures, agreement is visible for all depths, presenting maximum absolute errors of 0.8, 1.1 and 0.4ºC for the layers 3, 5 and 6, respectively. Also, we can see in the graph for layer 3 the perfect agreement of the two lines over the 24 h showing the good accuracy of the predictions. This layer is more influenced by the air temperature than the deeper ones and the model reflects that very well.

Considering that during the 1998 experiments, some inputs of the model were estimated, we could expect that some errors occurred. In spite of that the results obtained seem to be very reasonably and show, in general, good model performance.

#### 4.4.1.2.2 Validation with 2000 data

The results of the simulations for 15 May for the PV and CV greenhouses are presented in Figure 4.14 and 4.15, respectively. As explained before, ventilation management was achieved by opening the vents at 9:00 h with the same apertures for both greenhouses and by closing totally the vents in the CV greenhouse while in the PV

the ventilation area was only reduced, both at 17:00 hours. It is our goal to show that the model fits well with both ventilation managements.

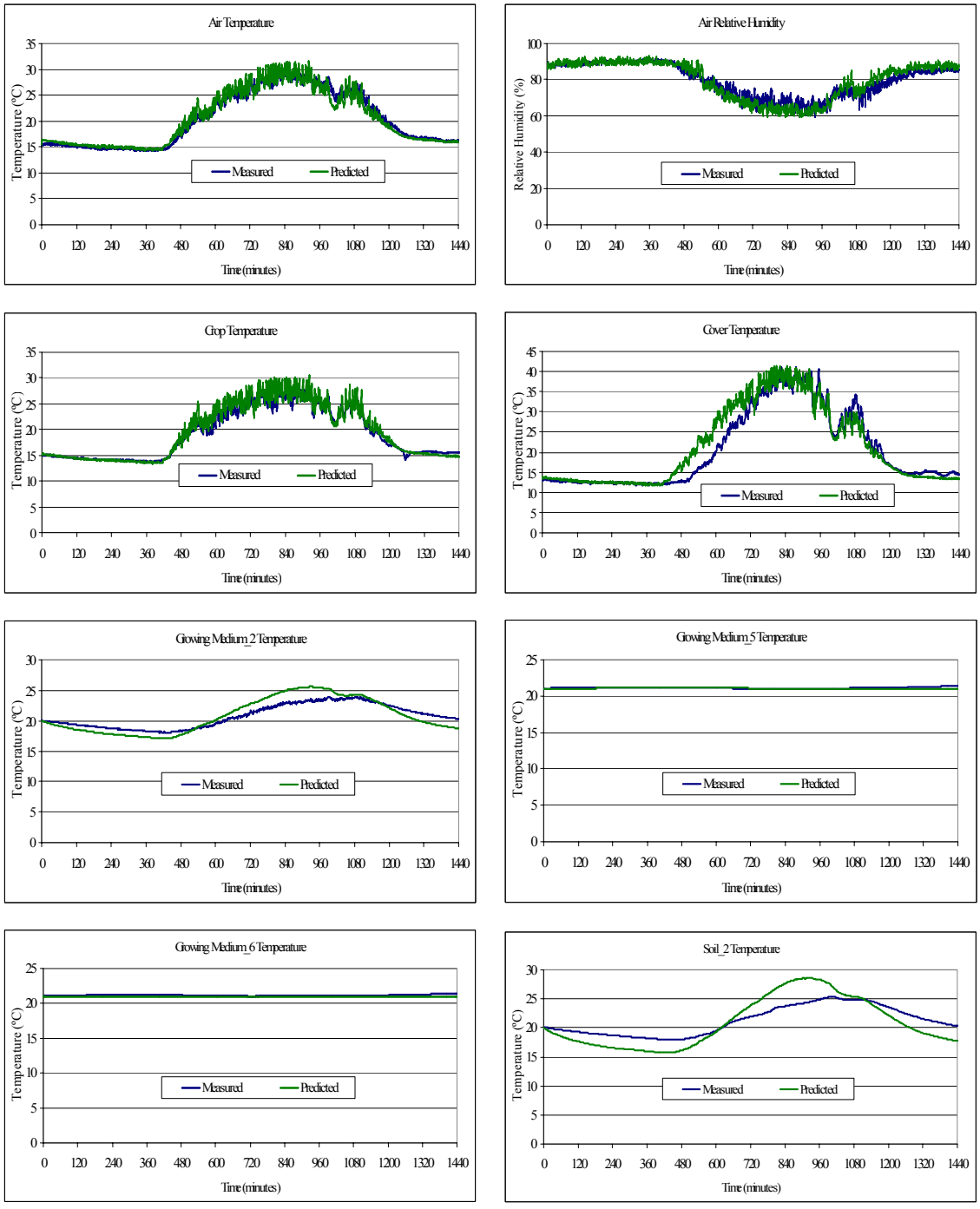



Figure 4.14 – Results of the simulation for 15 May 2000 for the PV greenhouse

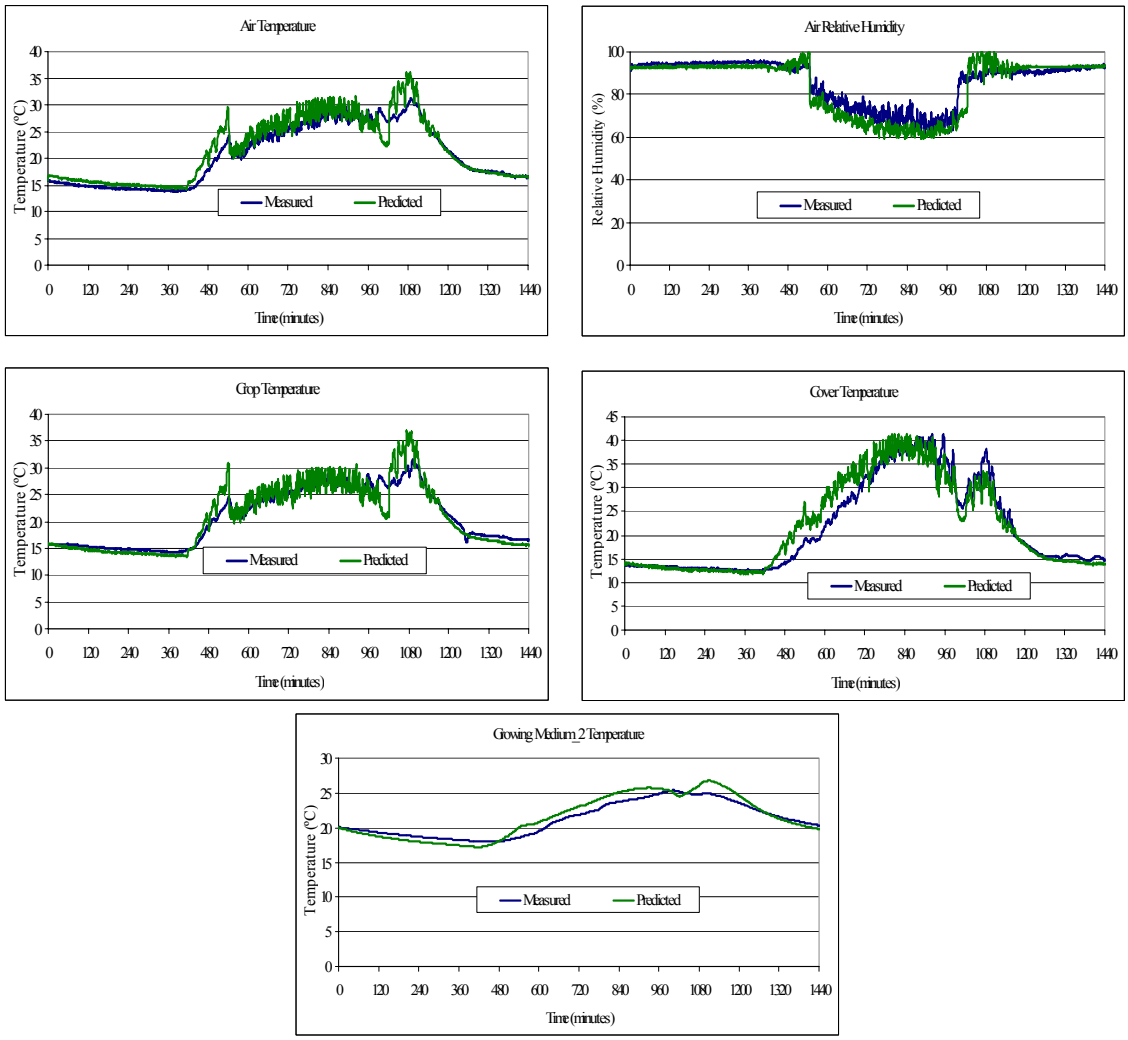



Figure 4.15 – Results of the simulation for 15 May 2000 for the CV greenhouse

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

In spite of this, the measured and predicted air and crop temperatures agree very well over the 24 h. The predictions of air temperature presented a maximum absolute error of 6.5ºC and 3.5ºC in the CV and PV greenhouses, respectively. Simulations of the relative humidity show a better performance during the night than during the day, which is explained by the more complicated sensible and latent energy balances that exist during the day, due to solar radiation and plant transpiration. However, for our purpose a good prediction of the night conditions is essential because this is when air relative humidity reaches the maximum values and can contribute to the occurrence of the *B. cinerea*. Maximum absolute errors of 20 and 12.7% were found in the CV and PV greenhouses, which seem reasonable, mainly because they occurred during the periods of changing the ventilation aperture.

Comparison between the predicted and measured cover temperatures showed similar results for both greenhouses, with maximum absolute errors of 8.5ºC during the day period. In fact, the night energy balance is very good, while some differences were found during the day. It seems the model overestimates the effect of solar radiation after the sunrise and takes some hours to readjust.

Concerning the growing medium temperature of layers 5 and 6, the simulations are almost perfect in both greenhouses, with a maximum error of 0.5ºC. Predictions for layer 2 (0.01 m depth) shows the model reaction to vents closure in the CV greenhouse, taking about 3 h to readjust, while in the PV greenhouse the vent reduction did not cause any response in the simulations. The maximum absolute error was found in the PV greenhouse (2.7ºC) during the day, slightly higher than in the CV house. However, it should be noted that the temperature of layer 2 was measured only in the PV greenhouse, and the data for the CV growing medium layer 2 was obtained as a function of the measured CV greenhouse air and growing medium layer 3 temperatures. This aspect could induce some erroneous conclusions, but in this case it seems not to be significant, since the performance is very good in both greenhouses.

Table 4.12 shows the simulation statistics parameters for the four days in May used to validate the model. The mean error shows, whether the model predicted higher or lower values than those measured by the positive or negative sign, respectively. The root mean square error is one of the statistical parameters which avoids the positive and negative deviations and allow a comparison with the results obtained by others. The adjusted determination coefficient can be an erroneous parameter if we do not have in mind the mathematical definition. In fact, some examples of this can be seen in Tables

4.12 and 4.13. Generally, the highest value of $r_a^2$ signifies the best agreement between the measured and predicted data. However, for example, for the growing medium and soil deeper layers, which we proved, graphically and also with the lower values for *RMSE*, to agree almost totally, it is possible to find $r_a^2$ near zero.

The air temperature is simulated accurately by the model for between 89 and 98% of the cases and the *RMSE* varied between 0.9 and 2.3ºC, which again is within a range of variation accepted as good in greenhouse climate modelling. Air relative humidity, which is accepted as the most difficult parameter to estimate, since it is directly connected with the air temperature, showed an *RMSE* which varied between 3.5 and 8.4%, which seems to be a good result.

Crop temperature is simulated with good results, presenting for these days a variation of the *RMSE* between 1.2 and 2.9ºC. Cover temperature is also predicted with good results, especially as it is another difficult parameter due to the measuring methodologies with the consequent sensor exposure to solar radiation. The *RMSE* varied between 2.6 and 3.7ºC, which is less than other results found in the literature.

Growing medium and soil temperatures for layers 4, 5 and 6 present values for the *RMSE* between 0.1 and 0.9ºC, which shows very good agreement and the power of the model to simulate these variables. The less deep growing medium layers, also showed good results, with *RMSE* values between 0.4 and 2.5ºC. This maximum value was for the surface layer, which was influenced by other factors, like the air temperature and possibly the sun. However, these values are perfectly acceptable. Comparison of the predicted and measured soil temperatures at the surface, and layers 2 and 3 showed a slightly worse result, with *RMSE* between 0.3 and 3.5ºC. This could be related with the fact that these values were not measured in the soil, but in the growing medium. As we know soil is much drier than the growing medium and using the same temperature can lead to errors. In fact, one could expect that real soil temperature will be higher during the day and lower during the night, which could approximate to the predicted results.

Figure 4.16 shows the results of the simulations for 18 June for the PV greenhouse. At this time of the year the ventilation was permanent for both greenhouses with the same ventilator areas during the day and night.

A general analysis of Figure 4.16 shows that the model performance is very satisfactory. There are no significant differences between the results of the model simulations for the CV and PV greenhouses, as expected, since the ventilation

management was the same. The following analysis will consider the results for the two greenhouses together.

Concerning the air temperature, the measured and predicted values were similar and the behaviour over the 24 h is consistent, presenting a maximum absolute error of 2.5ºC, which indicates a very good result. Simulations of the air relative humidity are slightly better during the night periods than during the day, with a maximum error of 13.5%, which again can be considered as good, especially for humidity predictions.

The results of the simulated crop temperature show good agreement with the experimental data, with a maximum absolute error of 5ºC. Measured and predicted cover temperatures show the same behaviour during the day, which indicates good performance of the model. The maximum absolute error was 8ºC during the day period, when the model overestimates the solar radiation effect.

The model performance, concerning the growing medium temperature is exactly the same as before, presenting a maximum absolute error of 1.9ºC for layer 2 and 0.9ºC for layers 5 and 6.

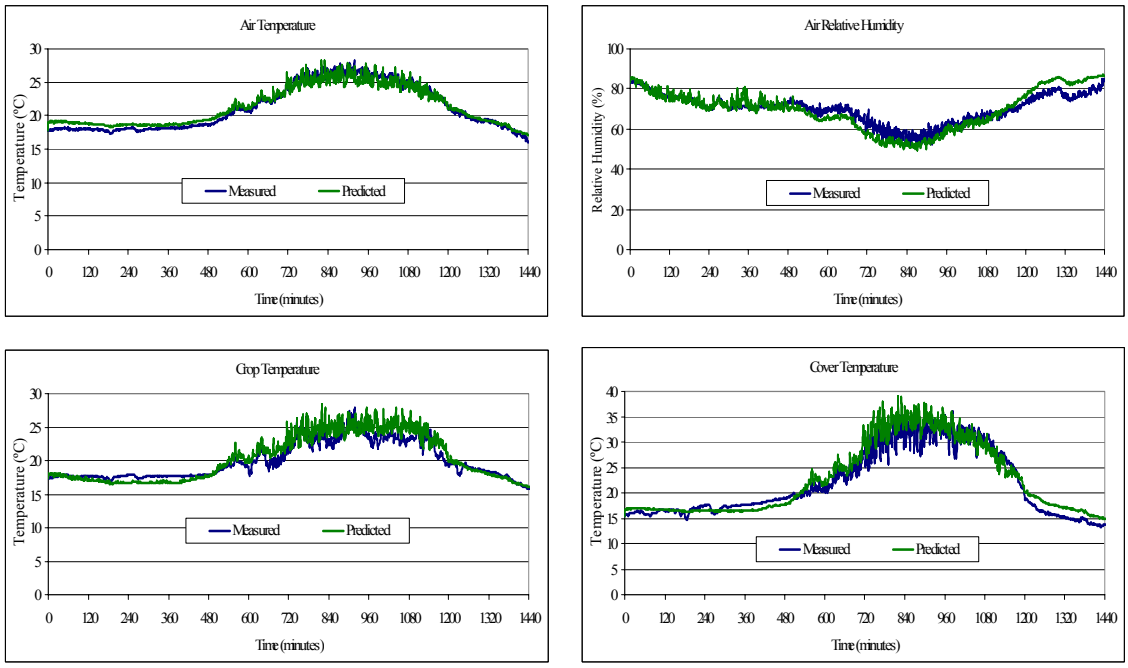



Figure 4.16 – Results of the simulation for 18 June 2000 for the PV greenhouse

Table 4.13 presents the simulation statistics parameters for the days of June used for the validation. In the majority of the results for air, crop and cover temperatures and air relative humidity, the mean error presents positive values, meaning the predictions

are higher than the experimental data. On the contrary, the predicted temperatures of the three first layers of the growing medium were always lower than the measured values.

The air temperature is simulated accurately by the model for between 93 and 98% of the cases and the *RMSE* varied between 0.8 and 1.9ºC, which is a good result. For the air relative humidity, *RMSE* changed between 4 and 10.5 %, which is acceptable, but slightly worse than the results obtained in May. However, during the first 3 days of June the measured relative humidity at 0:00 h, was very low (between 40 and 52%) for greenhouses with a tomato crop with a LAI of 4.4. In spite of the comparison with outside relative humidity and all the mathematical verifications, which have shown the calculations to be correct, it is our conviction that possibly these values do not represent the inside air relative humidity, and some unidentified problem occurred. During 18 June, the humidity reached expected values (near 80%) and the model performance was very good, with *RMSE* between 4 and 4.7%, which is more representative of the results.

The crop and cover temperatures showed good agreement between the predicted and measured data, with the variation of the *RMSE* between 1.0 - 3.9ºC and 1.9 – 3.4ºC, respectively. Growing medium and soil temperatures for layers 4, 5 and 6 gave values for the *RMSE* between 0.1 and 0.7ºC, showing the very good agreement between the measured and simulated data. The upper growing medium layers (1, 2 and 3) gave *RMSE* between 0.8 and 4ºC, which is slightly worse than the May results, but is still acceptable for the simulation of this greenhouse component.

Concerning the soil temperatures at the surface and layers 2 and 3, the *RMSE* varied between 0.4 and 4.2ºC, and the comments made about the results obtained for the May validation days, relating to the effects of solar radiation and the site of measurements also apply here.

Table 4.12 – Simulation statistics for predictions of the process components during the validation days of May 2000

| | 12 May 00 | | | | | | 13 May 00 | | | | | | 14 May 00 | | | | | | 15 May 00 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CV greenhouse | | | PV greenhouse | | | CV greenhouse | | | PV greenhouse | | | CV greenhouse | | | PV greenhouse | | | CV greenhouse | | | PV greenhouse | | |
| | *ME* | *RMSE* | $r_a^2$ | *ME* | *RMSE* | $r_a^2$ | *ME* | *RMSE* | $r_a^2$ | *ME* | *RMSE* | $r_a^2$ | *ME* | *RMSE* | $r_a^2$ | *ME* | *RMSE* | $r_a^2$ | *ME* | *RMSE* | $r_a^2$ | *ME* | *RMSE* | $r_a^2$ |
| **$t_{ia}$ (°C)** | 0.39 | 2.21 | 0.89 | -0.43 | 1.28 | 0.96 | 0.61 | 1.98 | 0.92 | -0.47 | 1.60 | 0.96 | 0.73 | 2.25 | 0.91 | -0.04 | 0.94 | 0.98 | 0.93 | 1.89 | 0.92 | 0.14 | 1.11 | 0.96 |
| **$RH_{ia}$ (%)** | -2.59 | 8.42 | 0.73 | -1.59 | 4.53 | 0.92 | -3.44 | 8.12 | 0.85 | -3.84 | 6.06 | 0.91 | -1.62 | 7.45 | 0.71 | -0.82 | 4.30 | 0.87 | -1.71 | 4.77 | 0.91 | 0.28 | 3.51 | 0.89 |
| **$t_{cr}$ (°C)** | 0.10 | 2.91 | 0.83 | 0.42 | 1.45 | 0.95 | 0.09 | 2.12 | 0.91 | 0.13 | 1.31 | 0.95 | 0.19 | 2.37 | 0.89 | -0.05 | 1.21 | 0.96 | 0.07 | 1.92 | 0.91 | 0.45 | 1.30 | 0.95 |
| **$t_{co}$ (°C)** | -1.58 | 3.68 | 0.94 | -0.63 | 3.38 | 0.91 | -0.02 | 3.12 | 0.93 | -0.27 | 3.71 | 0.89 | -0.09 | 2.64 | 0.95 | 0.35 | 2.68 | 0.94 | 0.36 | 2.76 | 0.92 | 0.77 | 2.88 | 0.92 |
| **$t_{gm1}$ (°C)** | -0.88 | 1.28 | 0.96 | -1.49 | 1.63 | 0.97 | -1.47 | 2.19 | 0.90 | -2.03 | 2.48 | 0.92 | -1.31 | 1.88 | 0.90 | -1.93 | 2.07 | 0.97 | -0.74 | 1.36 | 0.92 | -1.35 | 1.49 | 0.97 |
| **$t_{gm2}$ (°C)** | 0.36 | 1.34 | 0.93 | -0.21 | 1.10 | 0.88 | -0.18 | 0.91 | 0.94 | -0.39 | 1.30 | 0.82 | -0.14 | 0.88 | 0.95 | -0.42 | 1.12 | 0.93 | 0.32 | 0.95 | 0.95 | 0.07 | 1.21 | 0.88 |
| **$t_{gm3}$ (°C)** | -0.46 | 0.82 | 0.92 | -0.71 | 1.10 | 0.93 | -0.25 | 0.67 | 0.96 | -0.54 | 1.05 | 0.92 | -0.45 | 0.73 | 0.88 | -0.74 | 1.02 | 0.86 | -0.03 | 0.38 | 0.94 | -0.35 | 0.59 | 0.96 |
| **$t_{gm4}$ (°C)** | -0.53 | 0.78 | 0.22 | -0.63 | 0.89 | 0.07 | 0.21 | 0.34 | 0.60 | 0.12 | 0.22 | 0.82 | -0.17 | 0.47 | 0.70 | -0.28 | 0.59 | 0.50 | -0.09 | 0.13 | 0.93 | -0.23 | 0.29 | 0.67 |
| **$t_{gm5}$ (°C)** | 0.01 | 0.45 | 0.11 | -0.27 | 0.44 | 0.44 | 0.46 | 0.60 | 0.02 | 0.14 | 0.19 | 0.37 | 0.03 | 0.38 | 0.02 | -0.28 | 0.31 | 0.00 | 0.15 | 0.36 | 0.00 | -0.09 | 0.12 | 0.07 |
| **$t_{gm6}$ (°C)** | -0.21 | 0.36 | 0.40 | -0.23 | 0.38 | 0.56 | 0.12 | 0.19 | 0.34 | 0.12 | 0.19 | 0.35 | -0.18 | 0.21 | 0.02 | -0.19 | 0.22 | 0.02 | -0.15 | 0.18 | 0.05 | -0.17 | 0.19 | 0.02 |
| **$t_{s1}$ (°C)** | -1.83 | 2.59 | 0.96 | -2.15 | 2.80 | 0.95 | -2.31 | 3.54 | 0.80 | -2.49 | 3.37 | 0.86 | -1.88 | 2.96 | 0.92 | -2.08 | 2.93 | 0.96 | -1.18 | 2.72 | 0.89 | -1.37 | 2.62 | 0.95 |
| **$t_{s2}$ (°C)** | -0.79 | 1.97 | 0.92 | -1.16 | 2.12 | 0.87 | -0.80 | 2.16 | 0.85 | -1.22 | 2.42 | 0.79 | -0.52 | 2.06 | 0.95 | -0.90 | 2.15 | 0.92 | 0.04 | 2.10 | 0.90 | -0.34 | 2.19 | 0.86 |
| **$t_{s3}$ (°C)** | -0.80 | 1.04 | 0.90 | -0.94 | 1.21 | 0.89 | -0.52 | 0.75 | 0.95 | -0.68 | 0.96 | 0.91 | -0.61 | 0.77 | 0.91 | -0.76 | 0.92 | 0.89 | -0.16 | 0.31 | 0.97 | -0.32 | 0.43 | 0.96 |
| **$t_{s4}$ (°C)** | -0.60 | 0.88 | 0.05 | -0.68 | 0.96 | 0.01 | 0.17 | 0.27 | 0.74 | 0.11 | 0.20 | 0.84 | -0.27 | 0.54 | 0.59 | -0.35 | 0.62 | 0.43 | -0.13 | 0.17 | 0.86 | -0.23 | 0.28 | 0.70 |
| **$t_{s5}$ (°C)** | 0.02 | 0.45 | 0.16 | -0.27 | 0.44 | 0.51 | 0.47 | 0.61 | 0.00 | 0.15 | 0.20 | 0.35 | 0.05 | 0.38 | 0.00 | -0.28 | 0.30 | 0.00 | 0.15 | 0.37 | 0.00 | -0.09 | 0.12 | 0.07 |
| **$t_{s6}$ (°C)** | -0.21 | 0.36 | 0.26 | -0.22 | 0.38 | 0.88 | 0.13 | 0.20 | 0.32 | 0.13 | 0.20 | 0.36 | -0.17 | 0.21 | 0.03 | -0.18 | 0.21 | 0.02 | -0.15 | 0.18 | 0.02 | -0.16 | 0.18 | 0.02 |

Table 4.13 – Simulation statistics for predictions of the process components during the validation days of June 2000

| | 15 June 00 | | | | | | 16 June 00 | | | | | | 17 June 00 | | | | | | 18 June 00 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CV greenhouse | | | PV greenhouse | | | CV greenhouse | | | PV greenhouse | | | CV greenhouse | | | PV greenhouse | | | CV greenhouse | | | PV greenhouse | | |
| | *ME* | *RMSE* | $r_a^2$ | *ME* | *RMSE* | $r_a^2$ | *ME* | *RMSE* | $r_a^2$ | *ME* | *RMSE* | $r_a^2$ | *ME* | *RMSE* | $r_a^2$ | *ME* | *RMSE* | $r_a^2$ | *ME* | *RMSE* | $r_a^2$ | *ME* | *RMSE* | $r_a^2$ |
| $t_{ia}$ (ºC) | 1.29 | 1.76 | 0.98 | 1.11 | 1.68 | 0.98 | 1.41 | 1.90 | 0.98 | 1.16 | 1.69 | 0.98 | 0.57 | 1.17 | 0.93 | 0.40 | 1.02 | 0.94 | 0.42 | 0.91 | 0.97 | 0.16 | 0.76 | 0.97 |
| $RH_{ia}$ (%) | 1.92 | 10.10 | 0.68 | 2.69 | 10.54 | 0.67 | 1.27 | 9.57 | 0.78 | 2.66 | 9.59 | 0.80 | 0.94 | 7.98 | 0.68 | 2.44 | 8.07 | 0.70 | -2.39 | 4.73 | 0.89 | -0.18 | 3.99 | 0.90 |
| $t_{cr}$ (ºC) | 0.90 | 2.88 | 0.88 | 1.82 | 3.77 | 0.82 | 1.25 | 3.12 | 0.86 | 1.98 | 3.90 | 0.80 | 0.37 | 1.62 | 0.86 | 0.87 | 2.01 | 0.81 | -0.12 | 1.01 | 0.91 | 0.36 | 1.25 | 0.90 |
| $t_{co}$ (ºC) | 0.90 | 2.81 | 0.97 | 1.82 | 2.86 | 0.97 | 1.35 | 3.27 | 0.96 | 2.23 | 3.37 | 0.97 | 0.92 | 2.71 | 0.91 | 2.00 | 3.00 | 0.92 | -0.11 | 1.86 | 0.94 | 0.73 | 1.97 | 0.93 |
| $t_{gm1}$ (ºC) | -3.25 | 3.66 | 0.91 | -3.36 | 3.74 | 0.91 | -3.38 | 3.81 | 0.92 | -3.52 | 3.96 | 0.92 | -1.58 | 1.78 | 0.91 | -1.69 | 1.88 | 0.91 | -1.26 | 1.38 | 0.96 | -1.39 | 1.51 | 0.96 |
| $t_{gm2}$ (ºC) | -0.81 | 1.29 | 0.85 | -0.88 | 1.34 | 0.85 | -1.00 | 1.39 | 0.85 | -1.05 | 1.43 | 0.84 | -0.35 | 0.94 | 0.85 | -0.42 | 0.97 | 0.85 | -0.35 | 1.03 | 0.82 | -0.42 | 1.06 | 0.82 |
| $t_{gm3}$ (ºC) | -0.54 | 1.09 | 0.89 | -0.62 | 1.16 | 0.87 | -0.68 | 1.26 | 0.87 | -0.71 | 1.32 | 0.82 | -0.31 | 0.86 | 0.77 | -0.38 | 0.91 | 0.73 | -0.38 | 0.83 | 0.84 | -0.44 | 0.88 | 0.81 |
| $t_{gm4}$ (ºC) | 0.13 | 0.36 | 0.47 | -0.09 | 0.37 | 0.31 | 0.09 | 0.35 | 0.38 | -0.08 | 0.38 | 0.24 | 0.21 | 0.29 | 0.69 | 0.03 | 0.21 | 0.62 | 0.13 | 0.25 | 0.69 | -0.02 | 0.22 | 0.66 |
| $t_{gm5}$ (ºC) | 0.17 | 0.46 | 0.00 | 0.05 | 0.15 | 0.00 | 0.13 | 0.43 | 0.01 | 0.07 | 0.15 | 0.00 | 0.20 | 0.36 | 0.04 | 0.18 | 0.23 | 0.03 | 0.45 | 0.55 | 0.29 | 0.22 | 0.28 | 0.52 |
| $t_{gm6}$ (ºC) | -0.07 | 0.16 | 0.07 | -0.12 | 0.19 | 0.07 | -0.06 | 0.15 | 0.11 | -0.11 | 0.18 | 0.08 | 0.05 | 0.13 | 0.34 | 0.01 | 0.11 | 0.37 | 0.20 | 0.27 | 0.62 | 0.16 | 0.23 | 0.69 |
| $t_{s1}$ (ºC) | 1.66 | 3.32 | 0.98 | 1.56 | 3.32 | 0.98 | 1.81 | 3.42 | 0.98 | 1.67 | 3.30 | 0.98 | 0.73 | 2.24 | 0.96 | 0.38 | 2.40 | 0.91 | -0.02 | 1.70 | 0.95 | -0.15 | 1.73 | 0.95 |
| $t_{s2}$ (ºC) | 2.90 | 4.20 | 0.95 | 2.87 | 4.18 | 0.94 | 2.96 | 4.22 | 0.93 | 2.97 | 4.21 | 0.93 | 0.98 | 2.02 | 0.80 | 0.94 | 2.02 | 0.79 | 0.11 | 1.28 | 0.86 | 0.09 | 1.29 | 0.85 |
| $t_{s3}$ (ºC) | 1.37 | 1.75 | 0.92 | 1.30 | 1.67 | 0.92 | 1.38 | 1.76 | 0.92 | 1.37 | 1.72 | 0.92 | 0.79 | 0.84 | 0.95 | 0.72 | 0.78 | 0.95 | 0.18 | 0.38 | 0.97 | 0.13 | 0.37 | 0.97 |
| $t_{s4}$ (ºC) | 0.58 | 0.68 | 0.62 | 0.37 | 0.48 | 0.69 | 0.58 | 0.69 | 0.66 | 0.42 | 0.52 | 0.72 | 0.52 | 0.58 | 0.42 | 0.35 | 0.40 | 0.64 | 0.31 | 0.35 | 0.98 | 0.17 | 0.21 | 0.93 |
| $t_{s5}$ (ºC) | 0.24 | 0.44 | 0.14 | 0.09 | 0.15 | 0.25 | 0.20 | 0.40 | 0.21 | 0.12 | 0.16 | 0.33 | 0.26 | 0.38 | 0.22 | 0.22 | 0.27 | 0.14 | 0.50 | 0.59 | 0.33 | 0.25 | 0.31 | 0.48 |
| $t_{s6}$ (ºC) | -0.06 | 0.15 | 0.04 | -0.11 | 0.18 | 0.06 | -0.06 | 0.14 | 0.07 | -0.10 | 0.17 | 0.06 | 0.06 | 0.13 | 0.36 | 0.02 | 0.11 | 0.38 | 0.20 | 0.27 | 0.63 | 0.17 | 0.24 | 0.69 |

#### 4.4.1.3 Climate model final considerations

In this section the results obtained for all days used in the validation process, are globally analysed and compared with results published by other authors. Here we will only analyse the variables measured effectively, which means that soil temperature is excluded. The final climate model was tested against experimental data recorded during 1998 and 2000.

In order to evaluate the overall accuracy of the estimation made by the model an analysis was performed with all validation data and overall values of *ME* and *RMSE* were calculated. Table 4.14 gives the summary results for all the validation data.

Table 4.14 – Summary of the results for all validation days

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

The air temperature is simulated accurately, with overall values of *ME* of 0.3ºC and *RMSE* of 1.6ºC, which represents values accepted as good by several authors (Wang and Boulard, 2000; Cunha, 2003; Luo *et al*., 2005; Coelho *et al*., 2006). Air relative humidity, accepted as the most difficult parameter to estimate due to the dependence of the air temperature, showed *ME* of -0.8% and *RMSE* of 7%, these results are in accordance with others published by Navas *et al*. (1996), Zhang *et al*. (1997), Perdigones *et al*. (2005) and Salgado and Cunha (2005).

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

For the growing medium, the surface layer gave the worst result, with *ME* and *RMSE* values of -1.5 and 2.4ºC, respectively. The negative mean error shows that predicted values were lower than those measured. This was mainly during the day and is explained by possible sensor exposure to solar radiation. The results obtained for layers 2 and 3 showed better results, with *ME* values between -0.2 and -0.5ºC and *RMSE* values between 0.9 and 1.2ºC, which are in the same range as those presented by Navas (1996) and Wang and Boulard (2000). Growing medium temperatures for layers 4, 5 and 6 present values for the *ME* between -0.02 and 0.1ºC and for the *RMSE* between 0.2 and 0.5ºC, being in accordance with Navas (1996) and show the very good agreement and the power of the model to estimate the growing medium temperature.

Table 4.14 permits the comparison of the model performance for the day and night periods. In this case, the differences already mentioned are confirmed with the overall results. In fact, it is clear that the model fitted the data better during the night than during the day. These differences are particularly visible for the air, crop, cover and surface growing medium temperatures and for the relative humidity, with in general, the values of the *RMSE* being lower for the night period. This is related with the more complex day energy balance, as explained before. From the growing medium layer 2 and following model performance was similar.

In synthesis, the predictions agreed well with the recorded data, showing a slightly better performance during the night. In fact for the main goal of this thesis this is the most important period, since it corresponds with the period with the highest probability for the occurrence of high relative humidity conditions. It was shown that overall model performance is good and independent of ventilation management, but with a tendency to overestimate the effects of large changes in ventilator opening.

## 4.5 Conclusions

This chapter presented a brief literature review concerning the fundamentals of the greenhouse climate and greenhouse climate calculation models. A dynamic climate model was tested, adjusted and validated for the conditions which occurred during this experimental research.

Tests with the model permitted the identification of the necessary adjustments, which were mainly related with the ventilation and stomatal resistance sub-models, convection heat transfer coefficients and soil thermal characteristics. The revised final

climate model includes soil thermal properties and sub-models for ventilation and stomatal resistance adequate to this greenhouse-crop system and new expressions for the convection heat transfer coefficients, which were determined, by analysing experimental data recorded during 2000.

The final model was validated with data recorded in both years of experiments and good agreement between the predicted and measured data was obtained. This model can be used to estimate the greenhouse climate conditions, based on the weather conditions and on the greenhouse-crop system characteristics. Also, it has been shown that the modifications to the original model have improved its performance. In fact, it should be stated that generally, it is not possible to directly use a climate model obtained for different conditions, without adjustment of some parameters.

This climate model is combined with a *Botrytis* model in Chapter 6 and this will permit the development of an integrated system incorporating the prediction of microclimate conditions and outbreaks of *B. cinerea*.

# 5. *Botrytis cinerea* and infection conditions

## 5.1 Introduction

Pests and diseases affect the physiological processes of plant production in many ways. These organisms can reduce light, $CO_2$ and water input to the plant, affecting the rates of metabolism or growth process or may kill the complete plant. *Botrytis cinerea* Pers.: Fr. is the causal agent of grey mould disease, which causes severe losses in many vegetable and ornamental crops, and is one of the most important diseases in greenhouse production. The pathogen infects the leaves, stems, flowers and fruits. In greenhouse vegetables it causes necrotic lesions on leaves and in severe epidemics the entire foliage may be destroyed. Stems of plants can be infected either by invasion of the fungus through the petiole or by direct infection of wounds after deleafing, pruning and harvesting. Such infection may ultimately girdle the stem, killing the entire plant and cause substantial yield losses (Jarvis, 1989; Yunis *et al.*, 1990; Elad *et al.*, 1996). Infected flowers may abort and not produce fruits or the infection may remain quiescent in the developing fruit. On fruits, *B. cinerea* causes a typical rot that is frequently covered by a grey mould and that may serve as a source of inoculum within the crop. On tomatoes, the pathogen induces a characteristic symptom termed "ghost spot", which is characterized by small, necrotic lesions, usually surrounded by a bright halo (Verhoeff, 1970); this can make the fruit unmarketable.

The infection process involves three phases: germination, penetration and establishment. The two first phases are extremely dependent on the microclimatic conditions. In the third development of the mycelium is affected by the conditions within the host.

High relative humidity, free moisture on plant surfaces, moderate temperature (Smith, 1970; Blakeman, 1980), time and the activities of humans in terms of cultural and control practices (Agrios, 2005) are considered the most important factors which promote the infection by *B. cinerea*. Reports on precise moisture requirements for infection are contradictory and optimum temperatures for infection are considered to be between 10 and 20ºC, but infection could occur even at 2ºC and above 25ºC (Jarvis, 1980; Elad *et al.*, 1989; Salinas *et al.*, 1989). Conidia of *B. cinerea* require nutrients for germination and for subsequent germ tube growth on the host surface. Restricted availability of nutrients results in reduced infection rate (Yunis and Elad, 1993).

Growers usually use fungicides to control *B. cinerea*, both by spraying the whole canopy or by direct applications to the sporulating lesions on wounds. However, it has been shown that this pathogen may develop resistance against specific fungicides within a relatively short of time. Resistance to benzimidazoles, dicarboximides and others has been found (Elad *et al*., 1991; FRAC, 1998). One of the alternative methods to control grey mould in greenhouses is the prevention of canopy wetness by intensive heating or ventilation (Morgan, 1984). This is in general effective against infection of leaves, flowers and fruits, but not against stem infections, which can be initiated up to 10 weeks before the symptoms are observed (Wilson, 1963): this complicates management of the disease.

This chapter includes a literature review on the general characteristics of *B. cinerea* and the most important conditions required for its development in greenhouse crops. The methodology followed for the observations inside the greenhouses is presented and the results obtained in greenhouses with both permanent and classical ventilation. The main objective of this chapter is to show the effectiveness of nocturnal (or permanent) ventilation in reducing *B. cinerea* severity and incidence on tomato crop grown in unheated greenhouses.

## 5.2 Review of literature

### 5.2.1 Description of the fungus and symptoms of the disease

The *Genus Botrytis* was referred for the first time by Micheli in 1729 (Coley-Smith *et al*., 1980). In 1801 Persoon increased the knowledge about the fungus which was embodied in the G*enus Botrytis* Pers. (Ganhão, 1990; Herrera, 1993). *Botrytis cinerea* Pers. is the asexual or conidial form (*Class Deuteromicetos* or imperfect fungi) of the *Sclerotinia fuckeliana*, which was established as the perfect form of the pathogen by De Bary at the end of the XIX century.

Rosslenbroich and Stuebler (2000) mentioned that *Botrytis cinerea* Pers.: Fr. is one of the most interesting fungal pathogens because of its very unique characteristics, it can live pathogenically but also saprophytically, it can be very devastating in some crops but it can also be of some benefit under certain conditions. It can be found all over the world and it can infect almost every plant and plant part (Stall, 1991). Additionally,

it can cause early latent infections which damage the fruits after ripening. Conidia are easily windborne and can be blown from field to field.

Jarvis (1989) mentioned that fungi have specific and often different optimum environmental requirements for sporulation, dispersal, spore germination and infection. *Botrytis cinerea* Pers.: Fr. is a necrotrophic pathogen whose inoculum is enhanced from soilborn and debris-borne sclerotia and large saprophytic bases. It produces conidia at temperatures above 12ºC (best at about 15ºC) in unsaturated atmospheres, releases them by a hygroscopic mechanism in conditions of rapidly changing humidity, and generally infects plants, especially wounded plants, from conidia and occasionally ascospores in a film of water. The conidia germinate best at 20ºC, but germ tubes elongate faster at 30ºC. The optimum temperature for infection depends partly on the defense reactions of the host. *B. cinerea* can behave as a snow mould in forest seedlings and it can infect potato tubers at 3ºC, but infection mainly occurs between 15 and 25ºC. However, this fungus often infects plants directly from a saprophytically based inoculum such as in a fallen petal adhering to a leaf or fruit surface. It can also establish quiescent infections, which in tomato stems can last up to 12 weeks before becoming aggressive. This behaviour has profound implications in the design of prophylactic disease escape and therapeutic control measures.

Infection takes place through wounds, via decaying or dead plant tissue and by direct penetration of the undamaged host (Verhoeff, 1980). Stall (1991) reported the most characteristic sign of the disease was the numerous sporophores that grow from necrotic tissue. The diseased tissue presents a grey-brown appearance and clouds of spores can be shaken from the sporophores after periods of high humidity.

Lesions on leaflets progressively expand to include the whole leaf, then the petiole and finally the stem. Such lesions can girdle the stem and cause wilting of the plant above the lesion. Senescent petals are very susceptible. The fungus may grow from the infected petals into the sepals before the petals open, and from there it may grow into the developing fruit. Infected petals may remain attached to the fruit, and the fungus then grows directly on the fruit. *B. cinerea* causes necrotic lesions on flower buds and petals within 24 h after penetration of the flower (Kerssies *et al.*, 1998). Lesions on fruits are typical of soft rot, with decayed areas being whitish. Usually the skin ruptures in the centre of the decayed area, but is unbroken over the remainder. Sporophores develop only in the broken area, but eventually the whole fruit becomes affected and mummifies.

The presence of ghost spots on fruit is an unusual symptom of the disease. This can occur after spores germinate on the surface of the fruit, germ tubes penetrate it and the mycelium aborts. A small necrotic fleck appears along with a white halo, which is a whitish ring about 3-8 mm in diameter. The germ tube penetrates when the fruit is 1.5-3 cm diameter, but the full expression of the disease occurs at the mature green stage of development (Stall, 1991). Although no rot occurs with ghost spot, the many halos on the fruit make it unmarketable. On tomato plants the fungus affects leaves, stems, flowers and fruits. Leaves generally become infected through mechanical damage and physical contact with infected tissue. On fruits, both rot and ghost spot are common symptoms. Symptoms of the disease are variable depending on the plant organ affected. In tomato plants the characteristic symptoms are (Stall, 1991; Herrera, 1993):

- On the leaves, perfectly delimited concentric grey spots. This can cover a big part of the leaflet.
- On the stems, a well delimited cancer covered by a grey felt. The attack begins always in a nutritional basis or wounds and can be a small lateral cancer or be a necrotic lesion all over the stem. Tomatoes stem infection due to *B. cinerea* may result in a single grey mould lesion which can kill the whole plant.
- On the fruits, the soft rot is common and begins on the petiole and causes rottenness of the fruit.
- Ghost spot is a unique symptom in tomato fruits, which will not cause rottenness but decreases quality and commercial value.

Lesions caused by other fungi, physiological responses to high salt content in the soil or wind injury may mimic grey mould, but *B. cinerea* can be distinguished from these by the presence of sporophores and spores on the surface of the necrotic area.

From the time a spore of *B. cinerea* lands on the surface of a tomato leaf, the process leading to the development of a detectable lesion includes spore germination, growth of the germ tube into an infection hypha, penetration of the host, colonization of host tissue and symptom expression. The success of the whole process needs some conditions to be met for each successive step. Some authors have suggested that one or more of these steps require the presence, for an appropriate length of time, of free water on the host surface. This fungus develops optimally in conditions of high humidity and temperatures between 20 and 25ºC, the first factor being the most important.

Once the conditions for infection are recognized and their environmental parameters are defined, infection can be prevented simply by avoiding those conditions.

Jarvis (1989) suggested that in the case of *B. cinerea*, which is dependent on a water film for spore germination and infection, preventing temperatures from reaching the dew point is an effective mechanism of disease prevention.

### 5.2.2 Factors which influence *B. cinerea* infection and development

Plant disease develops as a result of the timely combination of several elements, a susceptible plant host, presence of the pathogen and favourable environmental conditions over a fairy long period of time. In fact, epidemics start with the initial introduction of the pathogen, when the available inoculum meets a susceptible host in a favourable environment.

Development of a grey mould epidemic is derived from several individual stages, germination of conidia, infection, spread of mycelium inside the infected tissue, sporulation and dispersal. The epidemic is influenced by all these stages as well by susceptibility of the host tissue, survival of conidia during the non growth season and the physiological status of the host. During the process of an epidemic it is difficult to identify the influence of meteorological conditions on each component of the disease (Jarvis, 1989).

Greenhouse conditions are different from those in open fields. Plants and pathogens can develop during seasons which restrict their development in the open field. Behaviour of the same disease on the same host may vary according to the type of greenhouse. Greenhouse factors that affect the variation of disease development comprise the type of heating system, the architecture of the greenhouse and the covering material, systems of ventilation and irrigation, the growth medium, the general crop management and factors influencing the interaction between pathogens and their hosts (Elad, 1999).

Elad and Shtienberg (1995) mentioned that the combining factors influencing the occurrence and severity of the disease were not very well understood. Most epidemics occur in cool and humid conditions, which favour infection and may also predispose the host to become susceptible (Jarvis, 1980). The most important climatic factors which influence plant infection with *B. cinerea* are high relative humidity, free moisture on plant surfaces and moderate temperatures (Smith, 1970; Blakeman, 1980). Other factors affecting plant infection are the light intensity and spectrum, soil moisture content, nutritional status, hormone treatments (Elad *et al.*, 1992) and mechanical

damage, such as from pruning and deleafing. These conditions are often amplified by the development of a luxuriant plant canopy, which reduces aeration and illumination and facilitates development of diseases.

The influence of air temperature, air relative humidity, the presence of free moisture on plant surface and wetness period on the infection of *B. cinerea* have been studied by Winspear *et al.* (1970), Nicot and Allex (1991), Elad *et al.* (1992), Wei (1995) and O'Neill *et al.* (1997, 2002).

In general, environmental control is easier in heated greenhouses, where the temperature is raised and the humidity reduced. In unheated greenhouses, temperature is reduced during the night period and consequently condensation on the greenhouse cover may occur. This results in the formation of drops, and dripping onto the plant canopy. Wetting the plants makes them more susceptible to disease development (Elad, 1999). This problem can be reduced by adding chemicals to the plastic which avoid dripping. Another phenomena which can contribute to the existence of free water on plant surfaces is guttation, this is observed on tomato leaves especially during the morning (Jarvis, 1980; Baptista *et al*., 1998).

#### 5.2.2.1 Plant or host susceptibility

Tomato plants are an important host for *Generus Botrytis* and it is possible to find some cultivars with different susceptibility, but none are resistant (Nicot and Allex, 1991; Elad and Shtienberg, 1995; Nicot and Baille, 1996; Nicot *et al*., 1996; Lamboy, 1997).

Several internal and external factors of a particular host play an important role in the development of the disease. Some plants present natural resistance to some pathogens, which prevent the disease infecting and developing. Also, the same plant at different ages can have different behaviour concerning the same pathogen. In conclusion, depending on the plant-pathogen combination and period of time, the disease might or might not develop (Agrios, 2005).

Stall *et al.* (1965) observed that more grey mould occurred on plants with dense foliage due to a more favourable microclimate for disease development. Jarvis (1977) reported that young tomato stem tissues, compared with old tissues, are more resistant to the growth of *B. cinerea* and also to the germination of conidia in their vessels.

Körner and Holst (2005) mentioned that lower leaves (older) in the canopy are often attacked and then the fungus can spread.

#### 5.2.2.2 Presence of inoculum

In greenhouse environments, conidia of *B. cinerea* are always present (Kerssies, 1994 *cit in* Körner and Holst, 2005). The inoculum may originate from the greenhouse itself or may be introduced from a distance. *B. cinerea* conidia can be introduced into the greenhouse by streams of air coming from outside. Other means of transmission are greenhouse tools, such as grafting implements or knives that contaminate plants while being used.

Once established on plants in the greenhouse, the primary focus of infection provides inoculum for secondary spread. The spores of airborne pathogens (e.g. downy mildew and grey mould) are produced in large quantities and generally under wet conditions but are released most readily when the humidity drops (Elad, 1999). In commercial greenhouse crops growers tend to cultivate the same crop every year, which can contribute to the establishment of the pathogen and an increase in damage every year.

The inoculum can remain from one year to another in the soil and can be spread by the wind and by equipment used for deleafing, etc. If both host and pathogen are present and the environmental conditions are appropriate the disease can develop.

In between growing seasons, in the absence of major hosts, the pathogens may face severe conditions. In the absence of hosts, *B. cinerea* survives in a saprophytic stage in soil or in organic materials such as plant debris, or it may grow on alternative hosts, including weeds. Also, the *B. cinerea* inoculum, in plant debris, is able to survive at high temperatures in semiarid countries (Yunis and Elad, 1989) or at low winter temperatures in the temperate zone (Palti, 1981 *cit. in* Elad, 1999).

Dead flowers and leaves could become a massive saprophytic base for inoculum if they remain on the surface of fruits, stems and leaves (Beck and Vaughn, 1949). Eden *et al.* (1996) reported that high inoculum concentrations increase infection on both flowers and leaf removal wounds. They demonstrated the practical importance of reducing inoculum, *i.e*. by removing the necrotic tissues; it can minimize the conidial load in the crop and contribute to disease control. Also, O'Neill *et al*. (2002) mentioned

that removing all dead leaves was more effective than removing only visible infected leaves.

#### 5.2.2.3 Plant nutrition

Plant nutrition is an important factor since it affects plant growth which influences pest and disease dynamics and which will affect yield (quantity and quality). Nutritional conditions cannot be disconnected from others factors, like environmental conditions, soil characteristics, irrigation, etc. Most of the studies concerning disease and plant nutrition are about the effects of calcium.

Calcium is an important factor in many enzymatic processes. It interacts with plant hormones and is a building block in the cell wall and middle lamella, where pectin is present. Thus, atmospheric humidity and salinity in the plant root environment influence the level of calcium and its distribution within the plant. If the physiological status of the plant is disturbed its susceptibility to pathogenic agents may be enhanced. Since both calcium and hormones affect membranes and meristematic tissues, interaction between hormones, calcium and microclimate, with respect to the susceptibility of host organs to disease can be expected (Shear, 1975 *cit. in* Elad, 1999). High humidity may lead to a decrease in transpiration, which may reduce the transport of calcium and other divalent cations, mainly because calcium is translocated during the daytime and almost exclusively in the xylem by the transpiration stream.

Increasing the calcium content in plant tissue inhibits the development of some diseases. An increase in the concentration of calcium in the fertilizer resulted in a significant reduction of grey mould of crops grown in perlite, rock-wool or volcanic gravel. The severity of ghost spot in tomato fruits was also decreased by calcium fertilization. Disease was reduced on tomato and pepper plants grown in perlite or in soil amended with fertilizers containing 21% calcium (Elad, 1999).

Stall *et al*. (1965) reported a positive relation between the percentage of phosphorous in the leaves and the amount of grey mould and a negative relationship between the percentage of calcium in the leaves and the amount of disease. Stall (1991) reported that grey mould is particularly severe on plants grown in acidic sandy soils with high water content. Liming acid soils to increase the calcium content of plants reduces the susceptibility of tomato to grey mould.

Lamboy (1997) suggested that the components of the fertilizer should change with growth stage. Some varieties are very sensitive to excess nitrogen, which reduces yield and causes the plants to be more susceptible to disease. For strong stems, the calcium and magnesium balance is very important.

#### 5.2.2.4 Presence of wounds on plants

*B. cinerea* sporulates on infected tissues under high relative humidity conditions, but usually does not invade healthy green tissue such as leaves and stems unless an injured or dead area is present. Penetration occurs through wounds, except on tissues with low resistance such as some flower petals (Kamoen, 2000 *cit. in* Körner and Holst, 2005). Any agent that causes a wound in a plant surface renders it very susceptible to *B. cinerea* infection (Jarvis, 1977; 1980).

In greenhouse crops, the routine operations of transplanting, deleafing, layering, pruning and harvesting can cause wounds or damage to plants. The pathogens can enter into tomatoes through wounds and natural openings such as stomata and leaf or fruit hairs (Smith, 1914; Strider and Konsler, 1965; both *cit. in* Wei, 1995). Deleafing is a usual practice in tomato crops, since it allows a better airflow between plants improving the microclimatic conditions, but at the same time provokes wounds, creating the ideal conditions for *B. cinerea* infection. Leaves and fruits which have been scorched can be potential sites for *B. cinerea* infection. When fruits or leaves are removed from the plant, a small drop of water may exude from onto the cut surface, which is eventually reabsorbed into the xylem. If conidia of *B. cinerea* were present in the last drop, they would enter into the xylem and become lodged in clumps some millimetres beneath the cut surface.

Jarvis (1992) reported that *B. cinerea* could often be found on broken cotyledons and pinch bruises on seedling stems and on wounds made by pruning. O'Neill (1994) found that some leaf infections of tomato plants followed physical damage and the fungus usually established itself on senescing or wounded plant tissue before developing to rot adjacent healthy tissue. Crop damage associated with moisture were the two most important factors in allowing the disease to take hold.

Nicot and Allex (1991) found that on intact tomato leaflets, conidia of *B. cinerea* failed to germinate in the absence of free water. In the presence of wounds they found that dry conidia germinated without the addition of free water and the frequency

increased significantly with increasing the degree of wounding. However, in the presence of free water they showed that the germination rate sharply increased with wetness duration of up to 7 h, above which it remained stable.

O'Neill *et al*. (1997) mentioned that susceptibility to infection decreased with increasing age of wounds on the stem. Infection of leaf scars on growing plants led to a slower development of lesions than in stems but the susceptibility persisted for at least 13 days. Crop management practices such as regular removal of dead leaves and increased air-movement at plant canopy level reduce *B. cinerea* (O'Neill *et al*., 2002).

Some studies have shown that pruning wounds on tomato plants are less likely to become infected by *B. cinerea* if leaves are cut close to the stem than if a fragment of petiole is left on the stem (Martin *et al*., 1994 *cit. in* Nicot and Baille, 1996).

#### 5.2.2.5 Environmental conditions

As mentioned before, the greenhouse microclimate often favours *B. cinerea* infection and development. Greenhouse climates are warm, humid and the air speed controlled, ideal for the development of many pests and diseases (Hussey *et al*., 1967 *cit. in* Wei, 1995). Knowing how these environmental factors influence disease infection and development may help to prevent it, thus minimising lesions and reducing chemical use.

The factors which affect disease development in the greenhouse are soil, air and leaf temperature, relative humidity, dew, soil moisture content and light (quality, day length and intensity). These can all be controlled to a certain extent depending on the environmental control facilities available. However, it should be noted that there are interactions between air temperature, relative humidity, dew deposition on the canopy, physiological status of the host, saprophytic micro flora and aggressiveness of the population of the pathogen, on the disease effect (Elad *et al.*, 1988). Interplay between these factors affects sporulation, dispersal, germination of conidia, penetration of the germ tubes and lesion development.

Environmental factors such as air temperature, relative humidity and dew deposition on the canopy, in isolation or combined, are usually considered the most important factors influencing disease infection and development. It should be noted that environmental conditions influence not only the pathogen but also host susceptibility, which seems to be increased at lower temperatures. Also, high humidity may provoke

physiological disorders due to several mechanisms and favours the incidence of grey mould (Jarvis, 1992; Nederhoff, 1997a).

#### 5.2.2.5.1 Temperature

*B. cinerea* has different optimal temperatures for each stage of its biological cycle, which makes it difficult to identify one temperature that can prevent the infection. Furthermore, sometimes the optimal temperature for plant growth is similar to the temperature for the pathogen development (Jarvis, 1992), which makes disease control more difficult. Conditions in the greenhouse influence the physiological status of the host organs and thereby affect the susceptibility to infection. Low night temperature and high relative humidity in the greenhouse predispose plants to disease.

In Table 5.1 are shown the temperature ranges for the different stages of biological cycle for *B. cinerea* presented by several authors.

Table 5.1 - Temperatures for growth phases of *Botrytis cinerea* (Jarvis, 1992)

| Growth phase | Min. temp. (ºC) | Max. temp. (ºC) | Optimum temp. (ºC) | Reference |
|---|---|---|---|---|
| Mycelium growth | | | 20-22 | Jarvis (1977) |
| | 0 | 35 | 24-28 | Shiraishi *et al.* (1970) |
| Sporulation | | | 15 | Jarvis (1977) |
| Spore germination | | | 20 | Hennebert and Gilles (1958) |
| | 2 | | 22-24 | Kochenko (1972) |
| | 7 | 26 | | Doran (1922) |
| Germ tube growth | | | 30 | Hennebert and Gilles (1958) |
| Appressorium formation | | | 27 - 28 | Morotchovski and Vitas (1939) |
| | | | 15 - 20 | Shiraishi *et al.* (1970) |
| Sclerotium formation | | | 11 - 13 | Morotchovski and Vitas (1939) |
| Sclerotium germination | | | 22 - 24 | Morotchovski and Vitas (1939) |

The effects of temperature on the growth of *B. cinerea* have been studied since 1912 (Jarvis, 1977). The optimum overall temperature for vegetative growth of tomato is around 20-25ºC, which is coincident with optimum temperature for growth of *B. cinerea* (Botton, 1974; Yoder and Whalen, 1975; Dennis and Cohen, 1976; all *cit. in* Wei, 1995). O'Neill *et al.* (1997) observed that optimum temperature for infection of tomato flowers, fruits and leaves was between 10 and 20ºC, but infection could occur even at 2ºC and above 25ºC.

An interaction seems to exist between time and temperature for *B. cinerea* spore germination. Haas and Wennemuth (1962) *cit. in* Wei (1995) reported that at 1ºC there was 80% germination in 40 days and at 10ºC there was 95% germination in 14 days.

Eden *et al*. (1996) reported that warmer growing temperatures reduced the incidence of *B. cinerea* on stem wounds, but increased losses from flower infection. This author considered that it was more important to reduce stem infection, as stem lesions can kill entire plants. Increased flower infection at higher temperatures is partially compensated by better plant growth and increased flower numbers.

#### 5.2.2.5.2 Humidity and wetness duration period

The water vapour content of air within a greenhouse is determined by various processes, of which crop transpiration, condensation, evaporation and ventilation are the most important. High relative humidity, free moisture on plant surfaces and cool weather are considered the most important environmental factors that promote infection by *B. cinerea*, but reports on the effects of humidity and leaf wetness duration, separately or in combination, are contradictory.

Conditions of high humidity (low VPD) prevail mainly in unheated greenhouses and is a major factor favouring leaf infection by *B. cinerea* conidia. Increased humidity and poor ventilation in the greenhouse have detrimental effects on plant development. Under these conditions translocation of some ions and hormones from the roots to the shoots and leaves is reduced (O'Leary and Knecht, 1972 *cit. in* Elad, 1999). *B. cinerea* spores contain little water and need to absorb it from the environment. Free moisture is probably necessary for fast germination and infection and short leaf wetness duration may provoke growth and development (Nederhoff, 1997a).

The deposition of dew is one of the most important factors which can affect disease. Dew is deposited as tiny droplets on the fruits, stems and leaves during condensation. When relative humidity is high these can accumulate into big droplets. Dense foliage will restrict the air movement and impede evaporation, so water deriving from condensation or guttation could persist, increasing the chances of fungal disease infection (Jarvis, 1980). The presence of dew and the persistence of free water on plant surfaces provide conditions in which fungal spores can germinate and infect the host (Jarvis, 1992; Lhomme and Jimenez, 1992).

Abundant, prolonged or repeated high moisture, whether in the form of rain, dew or high humidity is the most important factor for the development of diseases caused by fungi (Jarvis, 1980; Wei, 1995; Körner and Holst, 2005). Moisture not only promotes new succulent and susceptible growth in the host, but, more importantly, it increases sporulation of the fungi. The presence of high levels of moisture allows these to occur constantly and repeatedly leading to the disease. In contrast, the absence of moisture for even a few days prevents all of these events from taking place, so the disease is interrupted or completely stopped (Agrios, 2005).

Most fungal pathogens sporulate profusely in moderate to high humidity and they produce mucilaginous and hydrophilic spores most abundantly under very humid conditions (Jarvis, 1992). However, most species of *B. cinerea* seem to sporulate best in less than saturated atmospheres when the conidiophores are short and bear numerous spores that are rapidly dispersed (Paul, 1929; Hawker, 1950; both *cit. in* Wei, 1995).

Most fungi spores, responsible for the major diseases, will germinate only under high humidity or in free water. High humidity often leads to the condensation of moisture on aerial plant parts, and therefore the effect of free water is often difficult to separate from that of high humidity. The optimum levels of relative humidity to restrict the development of plant diseases are very difficult to define because they are influenced by the temperature (Elad, 1999). The minimum vapour pressure deficit considered optimal for growing and producing greenhouse crops is 0.5 kPa and is commonly used as a threshold for dehumidification (Nederhoff, 1998; Bartzanas *et al*., 2005). This is exactly the same value reported by Analitys (1977), as the value below which the rate of development of *B. cinerea* increases rapidly.

Elad *et al.* (1992) reported that infection by *B. cinerea* was promoted by relative humidity higher than 91% in a range of temperatures between 9 and 24ºC. The infection occurred 7 to 8 days before the symptoms were visible. Rippel (1930) *cit. in* Wei (1995) reported that spore germination was complete when the relative humidity was higher than 95%. For a relative humidity of 90% only 80 to 85% of the spores germinated, while at a relative humidity of 85% spore germination did not occur at all. This author also studied the combined effect of temperature and relative humidity on the spore germination. When the relative humidity was 95%, 80% of conidia germinated at 15 and 5ºC. At a temperature of 20ºC, there was 100% germination at 100% relative humidity, 85% germinated at 90% relative humidity and when the relative humidity was below 90% the germination was 0%.

Snow (1949) studied the germination of *B. cinerea* spores on dry nutrient gelatine. Germination and growth took place at relative humidity of 100, 95 and 93% but not at or below 90%. This author demonstrated that *B. cinerea* spores could only germinate at a relative humidity higher than 93%. Also, Allex (1990) had shown that in absence of water and without wounds germination was almost nil.

Kerssies (1994) *cit. in* Körner and Holst (2005) reported that necrotic *B. cinerea* lesions occur on flower buds and petals when the air relative humidity was higher than 95%. Eden *et al.* (1996) showed that flower infection increased as a function of increasing relative humidity. Interruptions of periods of high relative humidity with breaks of low relative humidity did not reduce infection. Also, their results indicated that maintaining relative humidity below 90% with heating and ventilation will reduce but not eliminate the infection of flowers. It must be noted that a low level of flower infection will produce aerial inoculum and contribute to further infection. These authors also reported that humidity control had only a small effect on the level of stem wound infection. O'Neill *et al.* (1997) mentioned that stem wounds could be infected even at a VPD as high as 1.3 kPa and stem infection developed at a similar rate under low and high VPD conditions. Also, fluctuations between low and high VPD had insignificant effects on stem disease development.

O'Neill *et al*. (2002) reported that when it is not possible to reduce the relative humidity inside the greenhouse by increased heating or ventilation (due to high outside humidity), fungicide treatment and other control methods should be considered, in the integrated approach to *B. cinerea* management.

In several host-fungus systems with *B. cinerea* it has been shown that high relative humidity may not be sufficient to result in infection and lesion development. In several cases a wetness period was necessary and the frequency of infections increased with the duration of the wetness period (Salinas *et al*., 1989).

Latorre and Rioja (2002) studied the effect of relative humidity at 20ºC and they found that no conidial germination occurred in the absence of free water, suggesting the need of free water under field conditions. However, infection caused by *B. cinerea* on grapes and other crops has been reported to occur under high relative humidity (>90%). They suggested that under high relative humidity it is very likely to have imperceptible condensation *in vivo*, providing the free water for germination and eventually for infection. Also, because of non uniform greenhouse temperatures Nederhoff (1997a)

mentioned that a measured relative humidity of 93% or higher is likely to result in 100% in colder spots and *B. cinerea* can be imminent.

Fletcher (1984) *cit. in* Meneses and Monteiro (1990) mentioned that epidemic development of *B. cinerea* is dependant upon prolonged periods of high humidity and surface wetness and it may be prevented if relative humidity can be maintained between 70 – 80%.

The activities of foliar pathogens are probably more closely related to the microclimate close to leaf surfaces than to the general environment, but the forms reflects some exchanges in the latter (Cotton, 1969 *cit. in* Winspear *et al.*, 1970). However, Winspear *et al.* (1970) observed that although the environment measured in aspirated screens was not the same as that closer to plants, the changes initiated by humidity controls clearly extended into the crop micro-environment. Limiting the periods of high humidity delayed and decreased the incidence of *B. cinerea*. These authors showed that the incidence of ghost spots caused by *B. cinerea* on tomato fruits could be reduced substantially in a greenhouse where dehumidification was activated whenever relative humidity became higher than 90%, while disease was almost totally inhibited in a regime of dehumidification set at 75%. The problem was the high cost of dehumidification.

On the other hand, Boulard *et al.* (2004) concluded that the air humidity conditions prevailing in the pest habitat are strongly disconnected from that of the ambient greenhouse air. Near the canopy surface the air was more humid than the greenhouse air, especially during the day time when the transpiration rate reaches the maximum.

Disease incidence increases with increasing leaf wetness duration. However spores are sensitive to desiccation and die after long periods of low relative humidity in the order of 60%. After short periods of dryness (about 2 h) spores continue germinating when the humidity becomes high again (Nederhoff, 1997a).

Some authors tend to considerer the availability of free water as the main single factor influencing the infection by *B. cinerea* (Blakeman and Atkinson, 1976). However, this is far from the consensus view. In fact, studies conducted by Ekundayo (1965) *cit. in* Wei (1995) showed that uptake of water is a prerequisite to spore germination. Conidia were shown to swell when immersed in water and they reached a maximum size after 3 h. In contrast, Ilieva (1970) and Wei (1995) showed that *B.*

*cinerea* conidia could germinate in the absence of free water in conditions of relative humidity higher than 85%.

Plants in wet conditions can experience increased incidence of grey mould caused by *B. cinerea* (Tonchev, 1972; Yunis *et al*., 1990). Hildebrand and Jensen (1991) observed that the infection severity increased with increasing wetness duration on tomatoes and that the temperature for maximum infection was 28ºC when they were wound inoculated.

Wei (1995) showed that, on fruit surfaces, the wetness duration was increasingly significant when the relative humidity was less than 94%. When the relative humidity was over 94%, 85% of fruits were infected irrespective of whether the wetness period was 1 h or 8 h. This author also reported that an individual condensation period was not always sufficient for the disease to develop. However, the surface wetness duration could be cumulative when short wet periods were interrupted by dry intervals. These cumulative wetness periods could be suitable for spore germination and sporulation because some fungal pathogens can survive for short periods without liquid water on surfaces, especially when the wetness duration is followed by a long period of relative humidity over 95%. These conditions were sufficient for disease development. This author also showed that *B. cinerea* spores could germinate in the absence of free water. There was complete spore germination at 95% relative humidity and above, germination was reduced for lower relative humidity and no germination occurred when the relative humidity was below 85%. Once infection is established the level of humidity or surface water is irrelevant because the fungus is inside the host, and can obtain moisture from the organism.

O'Neill *et al.* (1997) concluded that under dry conditions sporulation is suppressed, although development of stem infection can occur. A reduction in sporulation may slow the epidemic progress in a commercial greenhouse. Nicot and Allex (1991) showed that on intact tomato leaves the presence of free water is necessary for spore germination for at least 7 h.

#### 5.2.2.5.3 Soil moisture content / irrigation methods

McQuilken (2001) showed that the irrigation method affected the development of grey mould on cuttings and rooted pot plants of calluna. Disease was less developed on plants watered by sub-irrigation compared with watering from overhead, and this

was associated with the difference in leaf wetness. However, drip-irrigation did not reduce grey mould and this was explained by a more humid microclimate within the plant canopy, especially at the plant base, sufficient to encourage infection by *B. cinerea*. Sub-irrigation methods seem to be a useful component for integrated control of grey mould. However, sub-irrigation alone is unlikely to provide commercially acceptable disease control. Modifying irrigation practices to reduce leaf wetness and humidity can reduce the disease in some species of ornamental plants (O'Neill and McQuilken, 2000).

#### 5.2.2.5.4 Light

Hite (1973) *cit. in* Elad (1997) reported that control of light wavelengths in the greenhouse could reduce the build-up of inoculum of *B. cinerea* and thereby reduce grey mould epidemics. Several studies have been carried out to study the effect of light on sporulation of *B. cinerea* (Nicot *et al*., 1996; Elad, 1997). Various ranges of wavelength either promote or inhibit sporulation of *B. cinerea*. Near ultra-violet (300-400 nm) and far-red (> 720 nm) light induce sporulation, whereas blue (380-530 nm) light inhibits it (Tan, 1975 *cit. in* Elad, 1999). Reuveni *et al*. (1989) *cit. in* Elad (1999) reported the control of tomato grey mould by using a polyethylene cover which reduced the UV irradiation significantly.

Elad (1997) mentioned that in commercial greenhouses, the use of green-pigmented polyethylene partially reduced conidial load and grey mould was reduced by 35-75% on tomato and cucumber fruits and stems. However, the load of conidia in greenhouses is usually high, so the number of conidia is not a limiting factor in conventional greenhouses. So, suppression of sporulation may only delay epidemic development.

Nicot *et al*. (1996) showed that incubation of *B. cinerea* under a film containing additives that absorb near-ultraviolet light below 380 nm resulted in considerable inhibition in spore production. Also, in cucumber and tomato greenhouses in Japan (Honda *et al*., 1977) and in Israel (Reuveni *et al*., 1989), both *cit in* Nicot and Baille (1996), the use of near ultra-violet absorbing films resulted in reduced incidence of grey mould compared to the control films.

Polyethylene films enriched with vinyl acetate and/or aluminium silicate as a way to reduce infra-red transmittance, providing a thermal effect, raises the crop

temperature and decreases leaf moisture (Vakalounakis, 1992; Elad, 1999). An example was given by Elad *et al.* (1988), in non-heated cucumber greenhouses covered with different types of polyethylene films with and without infra-red blockers. Application of this technique showed that the non-persistence of dew on foliage was the limiting factor for grey mould development in a relatively dry winter. In this study, disease severity under different infra-red sheets was correlated with the duration of dew. In a rainy winter, dew periods were long and grey mould was correlated with accumulated degree hours near the optimum temperature for disease development (15-25ºC). Plants generally grow better under thermal films. In general, the thermal infra-red polyethylene covers reduce the duration of dew on plants but extend the duration of temperatures favourable for epidemics. This is one of the difficulties in disease control since it is necessary to know all the influencing factors and combine them in a way that allow reduction of disease without a negative influence on the crop.

#### 5.2.2.5.5 Environmental control techniques

Utilisation of climate management for disease control is increasingly regarded by tomato growers as one of the most efficient tools against *B. cinerea*. Terrentroy (1994) reported that symptoms of *B. cinerea* were less frequent in greenhouses equipped with climate regulation facilities.

The environmental conditions inside greenhouses that influence *B. cinerea* infection are mainly temperature, relative humidity and the availability of free water. Environmental control techniques like ventilation and heating, can contribute to the reduction of the humidity, and are powerful tools to provide the proper conditions, which in this case are those unfavourable to *B. cinerea* infection and development.

Conventional methods to control disease promoted by wetness include the reduction of atmospheric humidity by environmental manipulation (Winspear *et al*., 1970, Morgan, 1984; Clarke *et al*., 1994).

##### 5.2.2.5.5.1 Ventilation

Ventilation is one of the most important environmental control techniques used in greenhouses. It is primary related with the control of air temperature, but it also controls

relative humidity and carbon dioxide concentration. In unheated greenhouses, ventilation is the technique which controls the climate inside the greenhouse.

Under current practices ventilation and/or heating remain the principal means of avoiding excessive humidity (Nicot and Baille, 1996). Ventilation management is one of the factors which influence the interaction between pathogens and their hosts. In fact, ventilation or conversely restricted air movement and the concomitant increase in humidity, in addition to direct effects on disease may affect plant development, reproduction and yield, all of which may affect the disease indirectly (Elad, 1999).

Several regimes of natural ventilation have been tested to decrease humidity in unheated tomato greenhouses during winter and spring months in Portugal. These studies demonstrated that it was possible to reduce air humidity during the night with satisfactory tomato production (Abreu and Meneses, 1994; Abreu *et al*., 1994), if continuous ventilation was combined with modulation in the degree of opening of the ventilators.

Meneses and Monteiro (1990) reported that, as a rule, ventilation is increased during the day to avoid excessive heating and to eliminate water vapour and reduced at night to limit heat losses. As a result of this management, saturation of the greenhouse air may be reached, leading to condensation on the roof, walls and plants. These conditions usually remain until the following morning when the ventilators are opened.

Meneses *et al*. (1994) have shown that in unheated greenhouses nocturnal ventilation may help to reduce inside relative humidity, where the increase of heat loss is not as important as it is in heated greenhouses. Permanent night ventilation influences energy and water vapour balances, modifying soil, air and plant temperatures and also air moisture content. These authors reported that the most significant effect of night ventilation was the reduction of air relative humidity. Also, inside a non ventilated greenhouse at night they observed the occurrence of condensation on plants and internal walls of the greenhouse, often causing prolonged water dripping on to the plants, which may enhance the potential for infection by *B. cinerea*. If the outside temperature is not sufficiently low to damage the crop, nocturnal ventilation may decrease plant growth but it may also reduce the incidence of *B. cinerea*, which can compensate for the lower growth and lead to higher yields. Night ventilation reduced the incidence of *B. cinerea* and seems to be an effective way to reduce high relative humidity inside greenhouses and is the only alternative in unheated greenhouses. Depending on weather conditions, good ventilation management may avoid or at least reduce the number of sprays needed

to control *B. cinerea*. Lamboy (1997) reported that this disease can be controlled with low humidity, but it is hard to achieve in a plastic house on a rainy day.

Night ventilation gave significant reductions in the incidence of *B. cinerea* on tomato fruits, stems and leaves in experimental glasshouse tomato crops at a night temperature of 16ºC (Morgan, 1984). This author had shown that the increase in the incidence of *B. cinerea* was greater when night ventilation was restricted than when the night temperature was reduced by 3ºC. Nocturnal ventilation allowed the reduction of the mean relative humidity from 95 to 90% at 16ºC in a ventilated *versus* unventilated greenhouse. It was suggested that prophylactic effects of nocturnal ventilation could be even more effective during nights with lower temperatures. Also, it was demonstrated that continuous increased temperature and ventilation between dusk and dawn can reduce *B. cinerea*, although the routine use of this approach was prohibitively expensive. O´Neill *et al*. (2002) reported that application of extra heat and ventilation only when conditions are favourable to infection by *B. cinerea* is economically more attractive.

O'Neill *et al*. (1997) observed that increasing heating and ventilation are not effective ways to prevent *B. cinerea* on stems. The reason is that the moisture supplied by the wound itself may be sufficient to support conidia germination and the initial process of penetration. These methods are affective against infection of leaves, flowers and fruits, but not for stems. O'Neill *et al*. (2002) reported that increased air movement around plants had a small but significant effect on disease control. However, although the heat boost/ventilation treatments decreased relative humidity, the reduction was insufficient to prevent plants from being affected by grey mould. Even with these environmental control techniques there were times when the relative humidity was higher than 90 % for periods longer than 3 h. Greenhouse air relative humidity is very dependent on greenhouse ventilation. Boulard *et al*. (2004) found that reducing ventilation rate increased air humidity especially at the leaf level, contributing to conditions favouring disease development.

#### 5.2.2.5.5.2 Heating

In heated greenhouses, heating is another environmental control technique which can help to reduce relative humidity, helping to control *B. cinerea* infection. Gautier *et al*. (2005) have shown that leaves and fruits of cherry tomatoes close to heating pipes

have a 1 to 1.5ºC higher temperature during the day and night. O'Neill *et al.* (2002) reported that grey mould severity decreased when a heat boost was used to reduce relative humidity. Short duration heat-boost and ventilation treatments aimed at preventing periods of high humidity (>90%) for greater than 3 h within the plant canopy reduced the severity of grey mould in greenhouse crops of cyclamen.

Bartzanas *et al*. (2005) observed that with an air heater, condensation flux was reduced resulting in less condensation at the inner surface of the cover. The hot air stream produced by the air heater resulted in an increase of the air saturation vapour pressure, because the air heater increased the air dry bulb temperature without affecting the water vapour content of the air. Heating systems improved the control of both air temperature and humidity, particularly by keeping the inside air dew point lower than the cover temperature and preventing the occurrence of condensation on the plastic films. Also, keeping leaf temperature above the air dew point is an excellent way to prevent condensation which helps to limit some fungal diseases in greenhouses.

Perales *et al.* (2003) showed that combining heating and roof ventilation decreased relative humidity inside greenhouses. They mentioned that a good solution to avoid condensation is the combination of air heating and reduced ventilation. The disadvantage seems to be the higher energy consumption.

## 5.3 Disease observations in greenhouses

### 5.3.1 Observation methodology

An investigation was conducted to determine if ventilation management, especially nocturnal ventilation, would be suitable to avoid or at least reduce lesions caused by *B. cinerea* on tomatoes grown in unheated greenhouses. A tomato crop was grown during two seasons (1998 and 2000) in two identical greenhouses, one with classical ventilation (CV) and the other with permanent ventilation (PV), as explained in Chapter 2.

The methodology followed was the same in both years and for both greenhouses. Groups of four plants were selected at random (3 in 1998 and 4 in 2000) and the number of infected leaflets was counted on the experimental plants on 14, 22 May; 3, 14 and 22 June during the 1998 experiment and on 28 April; 3, 11, 16, 23, 31 May and 5, 9, 15 and 19 June during 2000. After counting the infected leaflets were removed from the

greenhouses. With this practice it was guaranteed that the same leaflets would not be counted at the next observation and at the same time it contributed to reducing the inoculum present inside the greenhouses. The period between observations was not regular since it was dependent on the level of the observed attack.

The size, number or position of the lesion was not considered. An infected leaflet was counted as one irrespective of whether the lesion was 1 or 10 $cm^2$, the number of lesions or their relative position on the leaflet. These data enabled the determination of Disease Severity (DS) as the number of diseased leaflets and Disease Incidence (DI) as the percentage of infected plants (Agrios, 2005). Disease Severity represents a physically output variable which was measured in the field and would be used for model calibration and validation. The incidence of ghost spots and stem lesions was only sporadic, so these were not considered.

As shown in Table 2.3 (Chapter 2) fungicides against grey mould were used only once in 1998 and three times during 2000. These chemical treatments were necessary to maintain the disease under control in the entire crop in both greenhouses, to minimise production losses and to simulate real production conditions. Since all the plants were under the same conditions, it was assumed that the treatments did not interfere with the objectives.

### 5.3.2 Statistical analysis methodology

Descriptive statistics were used to characterise the properties of the main variables. It was assumed that the data recorded at each observation date was independent from those at other dates, since all infected leaflets were removed after counting. Thus all the plants were back to the "zero point", without visual lesions. Since the data recorded was the number of infected leaflets without consideration of the size or number of lesions, this guaranteed independence of the data.

Data normality was evaluated by the Shapiro-Wilk test and the homogeneity of variances by Levene's test. Neither of the data sets recorded during the 1998 and 2000 experiments presented normal distribution and homogeneity of variances at a significance level of 0.05. However, as mentioned in Section 2.2.3, if data are balanced and samples are relatively large, analysis of variance is robust to departures from these assumptions (Underwood, 1998; Maroco, 2003; Pestana and Gageiro, 2005).

In order to evaluate if ventilation management had a significant effect on Disease Severity, an analysis of variance was conducted. Since data were recorded on several dates, there were two independent factors, ventilation and the observation date. A univariate analysis was performed to study the effect of each independent variable and the possible interaction between the two, on the dependent variable.

The dependent variable was studied in conformity of the general linear model (Eqn 2.2), where the two fixed factors were the ventilation (*V*) and the date of observation (*D*), according to the statistical model:

$$Y_{ijk} = \mu + V_i + D_j + VD_{ij} + \varepsilon_{ijk} \quad (5.1)$$

where $Y_{ijk}$ is the observation $k$ of the $i$ level of factor $V$ and $j$ level of factor $D$, $\mu$ the global mean, $V_i$ the effect of factor $V$, $D_j$ the effect of factor $D$, $VD_{ij}$ the interaction effect and $\varepsilon_{ijk}$ the random error of observation.

In all analyses, values for which the probability of occurrence was higher than 95% ($P < 0.05$) were considered as significant. When the interaction effect was found to be significant, the means were compared using the Syntax Editor of the SPSS programme. With this procedure it was possible to determine for each day, whether or not ventilation management had a significant effect on the number of infected leaflets. Concerning the individual effects, when differences were found between the means, post hoc tests and pairwise or multiple comparisons were selected to determine which means differed. Since the equal variance assumption was violated, and the samples were balanced, the appropriate post hoc test was Tamhane's test (Pestana and Gageiro, 2005; Corder, 2006).

The factor of the year was also considered for inclusion in Eqn 5.1, but it only increased the model complexity (3 independent variables) and did not give an increase in information or knowledge. In fact, since no relation existed between the observation dates of the experimental years, analysis combining these factors will not give any important information, so the year was not included.

However, we wanted to investigate if the level of disease attack was different in the two years. For this, the effect of the year was analysed using the same methodology as before, GLM with two fixed factors, which were in this case the year (*X*) and the ventilation (*V*),

$$Y_{ijk} = \mu + X_i + V_j + XV_{ij} + \varepsilon_{ijk} \quad (5.2)$$

where $Y_{ijk}$ is the observation $k$ of the $i$ level of factor $X$ and $j$ level of factor $V$, $\mu$ the global mean, $X_i$ the effect of factor $X$, $V_j$ the effect of factor $V$, $XV_{ij}$ the interaction effect and $\varepsilon_{ijk}$ the random error of observation.

The Disease Incidence was calculated and analysed using the same methodology, with year and ventilation management as the independent factors. These data verified the normality and homogeneity requirements, important aspects when using parametric tests for n < 30, which is the case. In each year, the DI which occurred in each greenhouse was compared to evaluate the effect of ventilation management, by means of a t-test, which is appropriate for comparing the means of two populations.

## 5.4 Results and discussion

### 5.4.1 *Botrytis cinerea* severity

Figure 5.1 shows photographs of the tomato plants with lesions in flowers, leaves, stems and fruits caused by *B. cinerea.*


Figure 5.1 – Visible symptoms caused by *B. cinerea* on the tomato crop. a) infected flower, b) infected leaflet and a detail of an infected flower over the leaf, c) infected leaflet, d) several removed infected leaflets, e) infected leaf, f) infected stem and leaf, g) infected stem due to wound caused by the tutor, h) infected tomato fruit (soft rot), i) ghost spot on tomato fruit

### 5.4.1.1 Analysis of the results obtained during the 1998 experiment

Figure 5.2 presents the total number of infected leaflets measured on the 12 experimental plants and Table 5.2 shows the mean severity for each date of observation and for both greenhouses. The first symptoms were visible on 12 May and the first date of data recording was 14 May. In both greenhouses, visual observation showed no strong severity, but a high level of attack in the CV greenhouse. Figure 5.2 shows two distinct periods concerning Disease Severity, the first being between 14 May and 3 June and the second defined by the dates of the two last observations.

The first period, corresponding to the different ventilation management period, showed some differences in DS in the two greenhouses, it was always higher in the CV greenhouse. The maximum number of infected leaflets occurred on 14 June, corresponding to the period when the ventilation management was already the same in both greenhouses. It is clear that the highest Disease Severity occurred when the ventilation was the same and some other factors were in synergy to favour *B. cinerea* development, such as deleafing with the consequent wounds, quantity of available inoculum and the environmental conditions. However, it seems that in this period, no big differences existed in DS between the two experimental greenhouses.

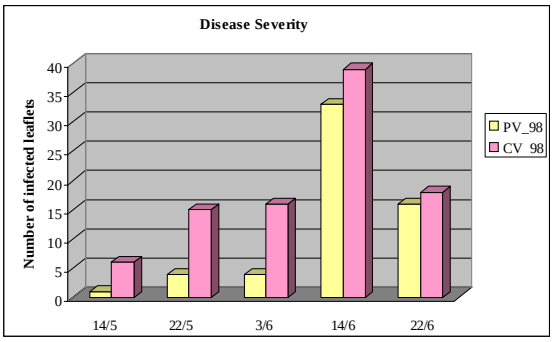



Figure 5.2 – Disease Severity obtained with the 12 experimental plants

Table 5.2 – Disease Severity ( $\bar{x} \pm se$ )

| Year | Date | Classical Ventilated Greenhouse | Permanent Ventilated Greenhouse |
|---|---|---|---|
| 1998 | 14 May | 0.50 ± 0.23 | 0.08 ± 0.02 |
| | 22 May | 1.25 ± 0.36 | 0.33 ± 0.10 |
| | 3 June | 1.33 ± 0.38 | 0.33 ± 0.10 |
| | 14 June | 3.25 ± 0.94 | 2.75 ± 0.79 |
| | 22 June | 1.50 ± 0.43 | 1.33 ± 0.38 |

$\bar{x}$ - mean, $se$ - standard error

Table 5.2 shows that the mean severity was higher in the CV greenhouse than in the PV house. However, the differences were not statistically significant. The univariate analysis, namely the test of between-subject effects showed significant individual effects of ventilation and observation date and a non significant interaction effect.

Table 5.3 shows the Disease Severity and the results of the variance analysis, conducted to study the effect of ventilation management for the total and the two sub-periods. The only period which showed a significant difference was the one from 14 May to 3 June, corresponding to different ventilation management in the two greenhouses. The DS in the PV greenhouse was approximately 25% of that in the CV greenhouse. In spite of the low level of *B. cinerea* attack, nocturnal ventilation reduced the infection in the permanently ventilated greenhouse. These results are in agreement with those of Morgan (1984) and Meneses *et al.* (1994). Also, O'Neill *et al.* (2002) reported that increased air movement around plants had a small but significant effect on disease control.

Table 5.3 – Disease Severity ( $\bar{x} \pm se$ )

| Period analysed | n | Classical Ventilated Greenhouse | Permanent Ventilated Greenhouse | P |
|---|---|---|---|---|
| 14 May - 22 June | 120 | $1.57 \pm 0.36$ | $0.97 \pm 0.34$ | 0.216 |
| 14 May - 3 June | 72 | $1.03 \pm 0.25$* | $0.25 \pm 0.14$* | 0.009 |
| 14 - 22 June | 48 | $2.38 \pm 0.81$ | $2.04 \pm 0.78$ | 0.768 |

* Significant differences $P < 0.05$, $\bar{x}$ - mean, $se$ - standard error

Table 5.4 presents the combined mean Disease Severity in the two greenhouses for each date of observation.

Table 5.4 – Disease Severity in both Greenhouses **(** $\bar{x} \pm se$ **)**

| Year | Date | Disease Severity |
|---|---|---|
| 1998 | 14 May | $0.29 \pm 0.13^{a}$ |
| | 22 May | $0.79 \pm 0.33^{a}$ |
| | 3 June | $0.83 \pm 0.28^{a}$ |
| | 14 June | $3.00 \pm 0.88^{b}$ |
| | 22 June | $1.42 \pm 0.66^{a}$ |

Different letters means significant differences $P < 0.05$

An analysis was made to find if the DS was different between each date of observation. The only significant difference between the combined values of Disease Severity in the two greenhouses occurred on 14 June. This could be associated with

deleafing, which was on 5 June, and could contribute to favour infection since it created wounds, as potential sites of fungus entrance to the plant, as reported by O'Neill (1994) and Wei (1995). The effect of the environmental conditions on Disease Severity will be discussed in the next chapter.

#### 5.4.1.2 Analysis of the results obtained during the 2000 experiment

The first symptoms of lesions caused by *B. cinerea* were visible on 25 April in both greenhouses. Visual observations showed that the tomato crop in the CV greenhouse suffered a more severe attack than in the PV greenhouse. By the end of May and after three fungicide treatments, the number of lesions caused by *B. cinerea* was still high in both greenhouses and the ventilation management was modified in order to improve disease control. As stated in Chapter 3, the spring of 2000 was very humid, which contributed to the early appearance and the high level of fungal attack. Also, there was a strong powdery mildew attack which certainly contributed to favour the infection by *B. cinerea* since it promoted plant fragility.

In Figure 5.3, the total number of infected leaflets measured on the 16 experimental plants is shown, for each date of observation and for both greenhouses. It is possible to observe that the maximum number of infected leaflets was always higher in the CV greenhouse than in the PV. These results are in agreement with others works obtained in the same type of greenhouse by Meneses *et al.* (1994).

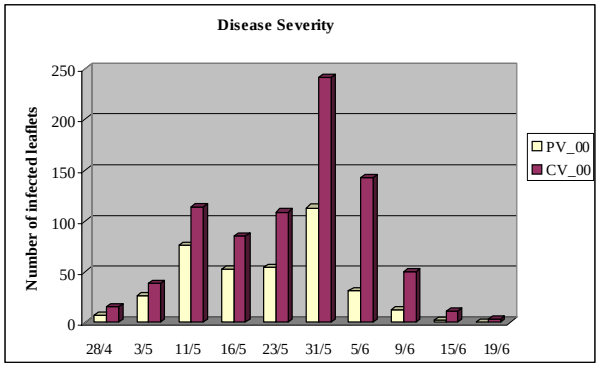



Figure 5.3 - Disease Severity obtained with the 16 experimental plants

Table 5.5 shows the Disease Severity and the results of statistical analyses conducted to study the effect of ventilation management on *B. cinerea* severity. The first period corresponds to all the data recorded in this experiment and the Disease Severities occurring in the CV and PV greenhouses were statistically different. We

believe this can be explained by the longer period with different ventilation management in the greenhouses than the period with the same ventilation (only June).

The period between 28 April and 5 June was studied as the period when the greenhouses had different ventilation managements. In fact, on 5 June the ventilation management was already the same in both greenhouses. However, the data recorded on that day was included in this analysis; since we considered those data were the result of conditions created when the ventilation treatments were different. It was found that ventilation management had a significant effect on Disease Severity. The PV greenhouse showed a DS approximately half that of the CV greenhouse, which can be explained by the different environmental conditions in the two greenhouses, mainly humidity and temperature. The Disease Severity will be related to these conditions later in Chapter 6.

The data recorded between 9 and 19 June, also showed a significant difference between the two greenhouses, which cannot be explained by ventilation management since this was exactly the same, from the beginning of June. This difference could be due to a higher quantity of inoculum present in the CV greenhouse, resulting from the higher attack that occurred during the previous period. These results are in agreement with Eden *et al.* (1996) and O'Neill *et al.* (2002), who state that a high quantity of available inoculum will favour higher level of infections. The last set of observations show no differences, which was expected since both greenhouses were under the same conditions.

Table 5.5 – Disease Severity ( $\bar{x} \pm se$ )

| Period analysed | n | Classical Ventilated Greenhouse | Permanent Ventilated Greenhouse | P |
|---|---|---|---|---|
| 28 April - 19 June | 320 | 5.06 ± 0.44* | 2.33 ± 0.29* | < 0.001 |
| 28 April – 5 June | 224 | 6.66 ± 0.55* | 3.21 ± 0.38* | < 0.001 |
| 9 - 19 June | 96 | 1.33 ± 0.29* | 0.29 ± 0.18* | < 0.001 |
| 15 - 19 June | 64 | 0.44 ± 0.24 | 0.06 ± 0.04 | 0.125 |

* Significant differences P < 0.05, $\bar{x}$ - mean, $se$ - standard error

Table 5.6 shows the combined Disease Severity data of both greenhouses for each date of observation. The objective was to check if differences existed in DS for the different dates of observation. Significant differences were found, P < 0.001, and some homogeneous groups were determined which are identified by the same letter, meaning

that no differences exist. It is possible to see that the results obtained for 31 May are very different from the rest. These differences between results obtained on different dates could be explained by the combination of several factors, such as the quantity of available inoculum, presence of wounds and different environmental conditions, along the experimental work.

The visible reduction in Disease Severity after 9 June could be the result of the combination of the climatic conditions and the deleafing effect, in spite of the wounds. Deleafing was done on 8 June and could contribute to better air circulation around plants avoiding the conditions of high humidity which favour *B. cinerea* infection and development.

Table 5.6 – Disease Severity in both Greenhouses **(** $\bar{x} \pm se$ **)**

| Year | Date | Disease Severity |
|---|---|---|
| 2000 | 28 April | $0.69 \pm 0.17^{c}$ |
| | 3 May | $2.00 \pm 0.35^{cd}$ |
| | 11 May | $5.94 \pm 0.72^{e}$ |
| | 16 May | $4.28 \pm 0.59^{de}$ |
| | 23 May | $5.09 \pm 0.68^{e}$ |
| | 31 May | $11.09 \pm 1.24^{f}$ |
| | 5 June | $5.44 \pm 1.03^{e}$ |
| | 9 June | $1.94 \pm 0.40^{cd}$ |
| | 15 June | $0.41 \pm 0.22^{c}$ |
| | 19 June | $0.09 \pm 0.09^{c}$ |

Different letters means significant differences $P < 0.05$

Since the test of subject effects showed a significant effect of the interaction between ventilation and observation date, we wanted to check if differences occurred for each date. For that we used multiple comparisons and the Syntax editor for designed comparison, which enabled the elimination of interaction effects, so the individual effects could be analysed. The results obtained are presented in Table 5.7, for each greenhouse and for each date of observation.

This methodology revealed that DS was different in the PV and CV greenhouses during 11, 23 and 31 May and 5 and 9 June. The two first days and 16 May, with different ventilation management, did not present significant differences and this showed that some other factors besides environmental conditions, such as available inoculum, presence of wounds or nutritional status, individually or combined,

influenced the development of *B. cinerea*. However, Disease Severity in the CV and PV greenhouses on 16 May was statistically different if we admit a level of significance of 90% ($P < 0.10$). The first two days of June, with the same ventilation management, showed significant differences, and again this could be explained by the high quantity of inoculum present in the CV greenhouse and because these data are the result of conditions which occurred earlier when the ventilation managements were different.

Table 5.7 – Disease Severity ($\bar{x} \pm se$)

| Year | Date | Classical Ventilated Greenhouse | Permanent Ventilated Greenhouse | P |
|---|---|---|---|---|
| 2000 | 28 April | 0.94 ± 0.31 | 0.44 ± 0.13 | 0.662 |
| | 3 May | 2.38 ± 0.54 | 1.63 ± 0.46 | 0.512 |
| | 11 May | 7.13 ± 0.89* | 4.75 ± 1.08* | 0.038 |
| | 16 May | 5.31 ± 0.91 | 3.25 ± 0.67 | 0.072 |
| | 23 May | 6.81 ± 1.01* | 3.38 ± 0.72* | 0.003 |
| | 31 May | 15.13 ± 1.27* | 7.06 ± 1.61* | < 0.001 |
| | 5 June | 8.94 ± 1.53* | 1.94 ± 0.64* | < 0.001 |
| | 9 June | 3.13 ± 0.46* | 0.75 ± 0.51* | 0.038 |
| | 15 June | 0.69 ± 0.44 | 0.13 ± 0.08 | 0.623 |
| | 19 June | 0.19 ± 0.19 | 0.00 ± 0.00 | 0.870 |

* Significant differences $P < 0.05$, $\bar{x}$ - mean, $se$ - standard error

#### 5.4.1.3 Comparison of *B. cinerea* severity during the two years of experiments

It was clear that the Disease Severity was completely different during the 1998 and 2000 experiments. Observation of Figure 5.4 shows a maximum mean Disease Severity of less than 4 during 1998 and around 15 during 2000. Also, the period with visible lesions was longer in 2000, and began three weeks earlier (in April) than in 1998. The number of fungicides treatments against *B. cinerea* was 1 in 1998 and 3 in 2000, which indicates the high severity of the disease in the second year.

Also, it is possible to observe a slightly higher ventilation effect in 2000. In fact, nocturnal ventilation gave a mean reduction of Disease Severity of about 60% in 2000 and 54% in 1998.

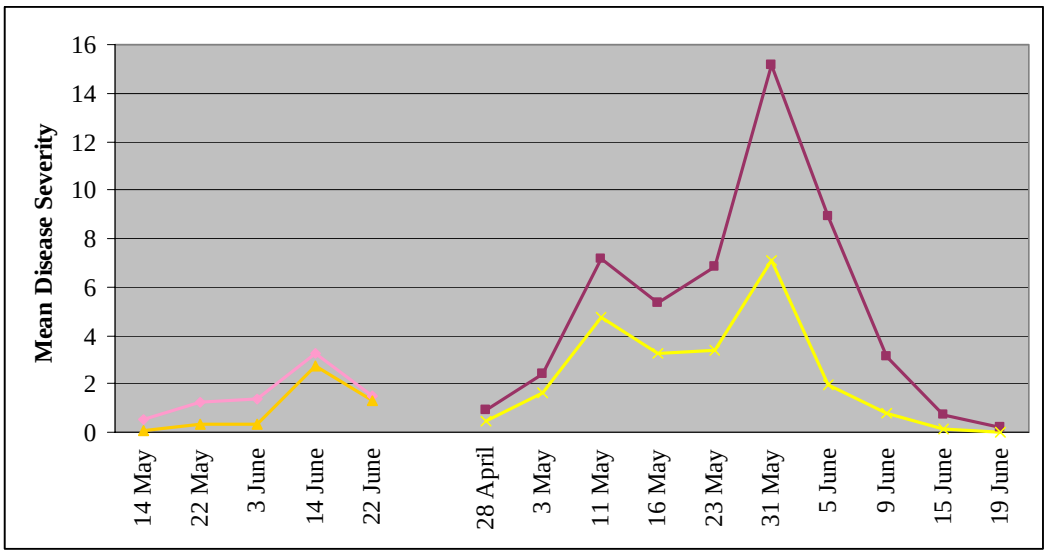



Figure 5.4 - Mean Disease Severity occurred during 1998 and 2000 experiments (**CV_98**, **PV_98**, **CV_00**, **PV_00**)

A statistical analysis was made in order to compare the Disease Severity in both years of experiments. The results obtained are presented in Table 5.8 and show the mean Disease Severity was about 2.9 times higher in 2000 than in 1998. Since tomato variety and growing techniques were the same in both years we believe this difference can be explained by the different climatic conditions which occurred during the two years. In fact, the climatic conditions were different. There was a non typical Mediterranean spring in 2000, with more rain than the usual with high humidity; in consequence it was favourable to fungal disease development, which includes *B. cinerea.* In 1998, the spring was drier, with near typical weather conditions and so was less favourable to fungal diseases.

Table 5.8 –*B. cinerea* Disease Severity for the two years of experiments

| Year | n | Mean | Standard error | Standard deviation | P |
|---|---|---|---|---|---|
| 1998 | 120 | 1.27* | 0.25 | 2.73 | < 0.001 |
| 2000 | 320 | 3.70* | 0.27 | 4.88 | |

* Significant differences P < 0.05

We also wanted to know if combining the two years data showed that ventilation management was still efficient in reducing *B. cinerea* severity. Table 5.9 shows that nocturnal ventilation reduced Disease Severity to about half that obtained with classical ventilation management. This is an important result for growers, who wish to reduce chemical use because of the negative environmental impact and cost.

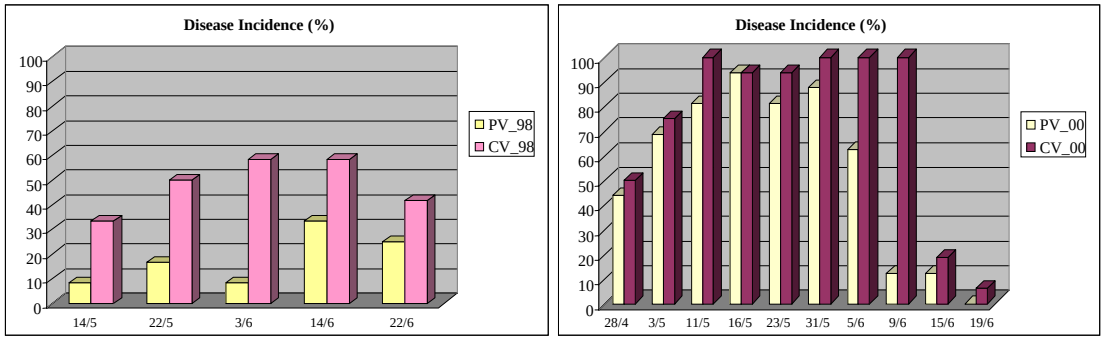
Table 5.9 – *B. cinerea* Disease Severity for the two greenhouses

| Greenhouse | n | Mean | Standard error | Standard deviation | P |
|---|---|---|---|---|---|
| CV | 220 | 4.11* | 0.35 | 5.19 | < 0.001 |
| PV | 220 | 1.96* | 0.23 | 3.44 | |

The interaction effect of year and ventilation was statistically significant (P = 0.02). Designed comparison showed that the Disease Severity in the CV greenhouse was different between 1998 and 2000 experiments (P < 0.001) and the same happened in the PV greenhouse (P = 0.035) and one of the causes could be the differences of ventilation in these two years. In 1998 the greenhouses were ventilated with both side and roof openings while during 2000 only side ventilators were opened. Air ventilation rates and air distribution patterns inside greenhouses are different if ventilation is achieved only with side ventilators or with both side and roof openings, as shown by Boulard *et al.* (1997), Bartzanas and Kittas (2006), Sase (2006) and Teitel *et al.* (2006). So, we can also expect differences at the plant level which influence disease development. However, other factors such as inoculum availability, plant nutrition status, irrigation, etc. could contribute to these differences.

### 5.4.2 *Botrytis cinerea* incidence

Disease Incidence, representing the percentage of infected plants, was calculated and the results are shown in Figure 5.5 for both years of experiments.




a) b)

Figure 5.5 - Disease Incidence in 1998 (a) and 2000 (b) experiments

It is evident that during 2000, Disease Incidence was much higher than in 1998, which is confirmed by statistical analysis (Table 5.10). Again this could be the result of the different environmental conditions which occurred in these years.

Table 5.10 –Disease Incidence (%) for the two years of experiments

| Year | n | Mean | Standard error | Standard deviation | P |
|---|---|---|---|---|---|
| 1998 | 10 | 33.3* | 6.0 | 18.8 | 0.014 |
| 2000 | 20 | 64.1* | 8.0 | 35.9 | |

* Significant differences $P < 0.05$

Figure 5.5a) corresponding to 1998, shows that the CV greenhouse had, for all observation dates, higher Disease Incidence than the PV house. The maximum DI occurred in the beginning of June with 58.3% of plants infected (CV greenhouse). In the same period the PV greenhouse presented the minimum DI (8.3%). In 2000 (Figure 5.5b), until the end of May, the DI was very similar in both greenhouses, but there were some differences in June. However, the DI in the PV greenhouse was always lower or equal to that in the CV. In this year the first peak was reached on 11 May in the CV greenhouse, when all the experimental plants were infected, then the Disease Incidence decreased after fungicide treatments, but by the end of May it was again 100%, and remained at that level until 9 June; while in the PV greenhouse *B. cinerea* incidence was decreasing. It seems clear that nocturnal ventilation was able to create better environmental conditions around the plants, which in this case were unfavourable to the disease development, but the level of attack was still high.

Table 5.11 shows the mean Disease Incidence calculated for each greenhouse, for each year and the result for both years. Statistical analysis permitted the conclusion that ventilation management had a significant effect on *B. cinerea* incidence during 1998 while no effect was found in 2000. However, looking at the results of both years, nocturnal ventilation contributed to a reduction of the Disease Incidence. So it is possible to recommend to growers that nocturnal ventilation is an efficient tool to reduce the disease.

Table 5.11 – Disease Incidence (%) for the two years of experiments and the two greenhouses

| Year | Greenhouse | n | Mean | Standard error | Standard deviation | P |
|---|---|---|---|---|---|---|
| 1998 | CV | 5 | 48.3* | 4.9 | 10.9 | 0.002 |
| | PV | 5 | 18.3* | 4.9 | 10.9 | |
| 2000 | CV | 10 | 73.8 | 11.4 | 36.1 | 0.238 |
| | PV | 10 | 54.4 | 10.0 | 34.9 | |
| 1998 + 2000 | CV | 15 | 65.3* | 8.3 | 32.0 | 0.044 |
| | PV | 15 | 42.4* | 8.7 | 33.5 | |

* Significant differences $P < 0.05$

## 5.5 Conclusions

Permanent or nocturnal ventilation was shown to have a great contribution to reducing Disease Severity on tomato leaves caused by *B. cinerea*, in both years of experimental work. In fact, in spite of a very humid spring during 2000, it was possible to reduce significantly the number of lesions (Disease Severity) caused by this fungus in the permanently ventilated greenhouse. This behaviour is explained by the better air circulation during the night which contributed to reduce humidity inside the greenhouse and in consequence in the canopy boundary. Disease Severity is a very important factor for growers, since it represents the level of attack of the disease. Their objective is to reduce it as much as possible and, if possible, without the use of chemicals, since this reduces production costs and environmental impact, which is becoming more and more important to consumers.

Disease Incidence was lower in the permanently ventilated greenhouse in 1998 but during 2000 the results were similar in both greenhouses. However, the combined results of both years showed that nocturnal ventilation was also able to reduce Disease Incidence. Disease Severity, by definition, has much great importance to growers than Disease Incidence. In fact, Disease Incidence may have little relationship with Disease Severity, since plants are counted as diseased whether they have one lesion or hundreds of lesions.

Ventilation management is an environmental control technique which can be used as a prophylactic measure, since it reduces the Disease Severity caused by *B. cinerea* on tomato crops grown in unheated greenhouses.

In this chapter the objective was to test the hypothesis that nocturnal or permanent ventilation is an environmental control technique which can be used in unheated greenhouse to reduce *B. cinerea* severity in tomato leaves. The results show that the hypothesis was proved to be true. In the next chapter the Disease Severity will be related with the climate conditions inside the greenhouse and the relations between them explained.

# 6. Development of a *Botrytis cinerea* Disease Severity prediction model

## 6.1 Introduction

In the previous chapters the greenhouse climate conditions and the occurrence of grey mould disease were individually analysed. Validation of the climate model was performed in Chapter 4 and it was proved that the model predicts accurately the greenhouse climate parameters while Chapter 5 proved the efficiency of nocturnal ventilation in reducing *B. cinerea* Disease Severity. In this chapter, the combination of climate conditions and *B. cinerea* severity is presented and the connection between greenhouse environmental conditions and disease occurrence is investigated. The main objective is to provide useful information about how and when to act to avoid or at least minimise disease occurrence.

This chapter includes a brief literature review of existing models to forecast outbreaks of *B. cinerea* in greenhouses. A model integrating climate parameters and disease severity was developed and validated (*Botrytis* model, BOTMOD). The modelling methodology was based on relating the Disease Severity with cumulative hours, within several ranges, of relative humidity and temperature, during different periods before the date of Disease Severity observations. Several relations were found and the models that showed the best fit are presented and analysed. A system combining the climate and *Botrytis* models was presented and leads to prediction of when the conditions would be favourable for *B. cinerea* development and also the expected grey mould severity. Finally some suggestions for the greenhouse crop-disease management are presented as a function of the conditions of relative humidity and the prediction of potential Disease Severity. An alert system is presented which would be useful to growers in helping them to decide the best timing of control interventions to prevent disease occurrence, by simply avoiding the conditions that favour its development.

## 6.2 State of the art

Modelling is a useful tool to study and to predict disease outbreaks. However, it has been widely used in pest management to simulate aspects of the biology, ecology and control rather than in disease management (Shipp and van Roermund, 1998). Also, it has been used more for disease forecasts in field crops such as onions, strawberrys

and grapes (Nicot and Baille, 1996; Jewett and Jarvis, 2001). Sutton *et al*. (1986) presented a forecast system to define the initial fungicide spray for managing *Botrytis* leaf blight on onions (BOTCAST) and de Kraker *et al*. (2005) developed a weather based warning system in an attempt to reduce fungicides use against *Botrytis* leaf blight in lily crops (BoWaS). In protected crops, disease forecasting systems are mainly concerned with ornamentals such as geraniums, gerberas and roses, grown in heated greenhouses. Tantau and Lange (2003) presented an anti-*botrytis* climate control management for a fuchsia crop and Körner and Holst (2005) developed a model for humidity control in order to avoid grey mould incidence and latent infections in chrysanthemums, both in heated greenhouses. For heated cucumber and tomato greenhouses, Clarke *et al.* (1999) developed a decision support tool for crop management, named Harrow Greenhouse Manager (HGM), which integrated knowledge on pest and disease management and also general production information.

Only a few references can be found for disease in unheated vegetable greenhouses and most of them are based on outside weather (Jewett and Jarvis, 2001). Yunis *et al.* (1990) studied the effects of air temperature, relative humidity and canopy wetness on grey mould in cucumber greenhouses. Multiple linear correlations were calculated for grey mould incidence and duration of air temperature and relative humidity in certain ranges, and leaf wetness. They found in the first stage of epidemics (infection), there was a high correlation between infected fruits and air temperature in the range of 11 - 25ºC and relative humidity in the range 97 - 100%. In the second stage (progress or development), disease incidence was better correlated with air temperature in the range 11 - 16ºC and relative humidity higher than 85%. Development of stem infection was correlated with air temperature in the range of 11 - 16ºC during the first phase while in the second it was closely correlated with relative humidity higher than 80%. It was concluded that the temperature effect was more significant than relative humidity or leaf wetness, which was attributed to the wet winter season, so that humidity was not a limiting factor.

Elad *et al*. (1992) studied the epidemiology of grey mould in cucumber greenhouses. They made an attempt to construct quantitative models relating the percentage of infected fruits with microclimate parameters, but the results were unsatisfactory. However, a qualitative approach allowed the development of a model to predict grey mould epidemics based on daily averages over the week preceding the

disease observation. The durations of wet foliage and temperatures between 9 and 21ºC during the night were found to be the most significant factors.

Yunis *et al.* (1994) developed a model for predicting outbreaks of grey mould in cucumber greenhouses using outside weather data. Outbreaks of grey mould occurred following weeks when the average period of leaf wetness exceeded 7 h $day^{-1}$ and night temperatures were between 9 and 21ºC for more than 9.5 h $day^{-1}$. It was suggested that the potential for outbreaks of grey mould epidemics could be reduced by measures which restrict the periods of leaf wetness. Shtienberg and Elad (1997) developed a strategy to help decide whether to spray a biocontrol agent or a fungicide, based on outside weather data, for cucumber and tomato greenhouses (BOTMAN). For each influencing parameter (rain quantity, number of rainy days, maximum and minimum temperatures, number of cloudy days and number of days with hot dry weather), an empirical severity value was established, reflecting their relative importance. Forecasts were converted to a disease risk index, by summing all individual severity values. The disease expectation was defined considering limits for the risk value as: >4.6, 2.5 to 4.5 and <2.4, corresponding to severe, moderate and low or no disease outbreak expected, respectively. The corresponding rules for decision making were chemical spray, biocontrol agent spray or no action at all. Milicevic *et al*. (2006) applied BOTMAN to evaluate integrated grey mould management in strawberry crops in open field and in greenhouse production.

Due to the high number of factors influencing the pattern of an epidemic, it is quite difficult to develop a generalised model for a particular crop and pathogen (Jewett and Jarvis, 2001). However, since there are some basic requirements for an epidemic development, it is possible and useful to develop models that could be used to predict those conditions. Chapter 5 presented the most relevant factors which contribute to *B. cinerea* infection and grey mould disease development. It was shown there are a large number of influencing factors, but it seems clear that environmental conditions, mainly relative humidity or dew presence and temperature, are of primary importance for spore germination and host penetration and consequently for the disease appearance.

## 6.3 Modelling methodology

A preliminary analysis of the evolution of air temperature and relative humidity before the first visible symptoms allowed the identification of when favourable climate

conditions for disease development started to occur and that was used to define the periods studied. During the 2000 experiment, several consecutive hours with relative humidity higher than 90% started 14 days before the first visible symptoms (which was on 25 April). Sixty percent of the disease observations data recorded during 2000 were used for modelling and 40%, and the 1998 data, were used for the validation process.

The modelling process consisted of relating Disease Severity with the duration of relative humidity and temperature in specific ranges, for several periods. Cumulative duration of the climate parameters over several time intervals, prior to the dates of disease observation: 4 to 7, 5 to 8, 8 to 11, 10 to 14 and 14 to 18 days, were analysed. The relations obtained were not statistically significant and had no biological meaning. Cumulative duration was then analysed for periods changing between 5 and 18 days before the dates of counting the number of infected leaflets with *Botrytis*. In these cases some results were significant and made biological sense. Interpretation of the results was based on the knowledge of the factors influencing the phenomenon under study. For instances it is well known that high values of relative humidity are favourable for disease development, so relations presenting negative coefficient in these ranges were considered as having no biological meaning.

Different ranges of relative humidity and temperatures were studied, individually and in combination: RH < 60%, RH > 70%, RH > 75%, RH > 80%, RH > 85%, RH > 90%, RH > 95%, RH > 98%, RH9598 (between 95 and 98%), RH9095, RH8590, RH8085, t < 8ºC, t < 10ºC, t > 15ºC, t > 20 ºC, t > 25ºC, t810 (between 8 and 10ºC), t1015, t1520, t2025. Several relations were obtained by regression analysis, using the backward routine of SPSS, which allowed the identification of the significant variables, for each period. Since results obtained by linear regression showed good representation of the data, non-linear models were not tested. The models selected for the validation procedure were chosen based on the criteria of the highest $r_a^2$ and the lowest *RMSE* (standard error of the estimate). Additionally, and to select the final model, *RMSE* of the model estimation was compared with *RMSE* resulting from the comparison between the predicted and the recorded values. The most accurate model is the one that presents similar values. All the necessary assumptions to use regression analysis were verified, either by residuals analysis (normality, variance homogeneity and non correlation) or by multi-collinearity tests.

For modelling purposes air temperature and relative humidity were used, inspite of knowing that the microclimate in the canopy is not exactly the same as in the greenhouse air. However, we believe these results could be interesting for growers as most of them measure air temperature and relative humidity in their greenhouses, and not leaf or crop temperatures. In fact, plant temperature is quite difficult to measure and is not commonly measured in commercial greenhouses. As mentioned before, plant temperature is not a unique value, since different parts of the plants may exhibit a wide range of temperatures, depending on the plant organ and its location.

## 6.4 Results and discussion

### 6.4.1 BOTMOD development and validation

In the first approach, the correlations obtained enabled identification of the most significant ranges of temperature and relative humidity which influenced grey mould severity. In fact, it was found that for all ranges with RH lower than 90%, the correlation coefficient was negative, indicating that disease was favoured only by conditions of RH higher than 90%. Concerning the temperature, it was identified that periods with temperatures lower than 10ºC were unfavourable for the disease and the opposite occurred for temperatures higher than 15ºC.

Table 6.1 shows some of the models obtained and the respective statistical parameters. It is visible that for less than 13 days, $r_a^2$ decreases significantly and increases the *RMSE*. This seems to indicate that Disease Severity was closely related with the climate conditions which existed several days before the observations. The results of the Durbin-Watson test, typically around 2, signifies that the residuals were not correlated (Pestana and Gageiro, 2005), which is one of the conditions required when using regression analysis.

From these models, those presenting the highest $r_a^2$ and the lowest *RMSE* were selected for validation with different data than those used for model development. Table 6.2 presents the models selected and used to predict Disease Severity. The predicted and recorded values were compared to evaluate model performance and finally the model that gave the best fit to the data was selected. Table 6.3 shows the results of the validation process achieved with measured climate data.

Table 6.1 – Models obtained by regression analysis

| Days before | Model | Correlation | $r_a^2$ | *RMSE (see)* | d |
|---|---|---|---|---|---|
| 18 | BOTMOD_18.1 | DS=f(RH90, t10, t2025) | 0.86 | 1.61 | 2.38 |
| | BOTMOD_18.2 | DS=f(RH90, t10) | 0.81 | 1.87 | 2.11 |
| 17 | BOTMOD_17.1 | DS=f(RH90, t10, t2025) | 0.90 | 1.36 | 2.44 |
| | BOTMOD_17.2 | DS=f(RH90, t10) | 0.83 | 1.77 | 2.26 |
| 16 | BOTMOD_16.1 | DS=f(RH90, t10, t2025, RH8590) | 0.93 | 1.11 | 2.74 |
| | BOTMOD_16.2 | DS=f(RH90, t10, t2025) | 0.91 | 1.29 | 2.47 |
| | BOTMOD_16.3 | DS=f(RH90, t10) | 0.82 | 1.85 | 2.08 |
| 15 | BOTMOD_15.1 | DS=f(RH90, t10, t2025, RH8590) | 0.95 | 0.99 | 2.28 |
| | BOTMOD_15.2 | DS=f(RH90, t10, t2025) | 0.94 | 1.02 | 2.15 |
| | BOTMOD_15.3 | DS=f(RH90, t10) | 0.80 | 1.90 | 1.94 |
| 14 | BOTMOD_14.1 | DS=f(RH9095, t810, t2025, RH8590, t1520, RH7075) | 0.97 | 0.71 | 2.11 |
| | BOTMOD_14.2 | DS=f(RH90, t10, t2025, RH8590) | 0.96 | 0.89 | 3.11 |
| | BOTMOD_14.3 | DS=f(RH90, t810, t2025) | 0.95 | 0.93 | 1.83 |
| | BOTMOD_14.4 | DS=f(RH90, t10, t2025) | 0.93 | 1.18 | 2.49 |
| | BOTMOD_14.5 | DS=f(RH90, t10) | 0.84 | 1.70 | 2.10 |
| | BOTMOD_14.6 | DS=f(RH9095, t10, t2025, RH8590) | 0.92 | 1.22 | 1.96 |
| 13 | BOTMOD_13.1 | DS=f(RH90, t10, t20) | 0.86 | 1.63 | 1.97 |
| | BOTMOD_13.2 | DS=f(RH9095, RH8590, t810, t2025) | 0.90 | 1.37 | 2.47 |
| | BOTMOD_13.3 | DS=f(RH90, t810) | 0.78 | 2.03 | 2.24 |
| | BOTMOD_13.4 | DS=f(RH90, t10) | 0.76 | 2.11 | 2.38 |
| | BOTMOD_13.5 | DS=f(RH90, t10, t20) | 0.86 | 1.63 | 1.97 |
| | BOTMOD_13.6 | DS=f(RH90, t10) | 0.76 | 2.11 | 2.38 |
| | BOTMOD_13.7 | DS=f(RH9095, t10, t2025, RH8590) | 0.88 | 1.51 | 2.61 |
| 12 | BOTMOD_12.1 | DS=f(RH90, t810) | 0.65 | 2.55 | 2.40 |
| | BOTMOD_12.2 | DS=f(RH90, t10) | 0.61 | 2.69 | 2.38 |
| | BOTMOD_12.3 | DS=f(RH90, t10, t2025) | 0.58 | 2.78 | 2.37 |
| | BOTMOD_12.4 | DS=f(RH90, t10, t1520) | 0.61 | 2.69 | 2.08 |
| | BOTMOD_12.5 | DS=f(RH90, t10, t1025) | 0.73 | 2.23 | 1.78 |
| | BOTMOD_12.6 | DS=f(RH90, t10, t15) | 0.73 | 2.23 | 1.78 |
| 11 | BOTMOD_11.1 | DS=f(RH90, t810, t1015) | 0.67 | 2.45 | 1.72 |
| | BOTMOD_11.2 | DS=f(RH90, t810) | 0.60 | 2.73 | 2.30 |
| | BOTMOD_11.3 | DS=f(RH90, t25, t1025) | 0.70 | 2.34 | 1.53 |
| | BOTMOD_11.4 | DS=f(RH90, t15) | 0.69 | 2.39 | 1.56 |
| 10 | BOTMOD_10.1 | DS=f(RH90, t25, t2025, RH8590) | 0.78 | 2.03 | 1.66 |
| | BOTMOD_10.2 | DS=f(RH85, t25, t1025) | 0.67 | 2.48 | 1.74 |
| | BOTMOD_10.3 | DS=f(RH90, t20) | 0.68 | 2.42 | 1.60 |
| | BOTMOD_10.4 | DS=f(RH90, t25) | 0.60 | 2.72 | 1.63 |
| | BOTMOD_105 | DS=f(RH90, t10, t20) | 0.68 | 2.44 | 1.96 |
| | BOTMOD_10.6 | DS=f(RH90, t25,RH8085) | 0.70 | 2.36 | 1.59 |
| 9 | BOTMOD_9.1 | DS=f(RH90, t10,RH8590) | 0.65 | 2.53 | 2.19 |
| | BOTMOD_9.2 | DS=f(RH90, t10) | 0.60 | 2.72 | 2.19 |
| | BOTMOD_9.3 | DS=f(RH90, t10, t25) | 0.72 | 2.28 | 2.04 |
| | BOTMOD_9.4 | DS=f(RH90, t10, t20) | 0.64 | 2.57 | 2.13 |
| | BOTMOD_9.5 | DS=f(RH9095, RH95,t20) | 0.59 | 2.76 | 1.71 |
| | BOTMOD_9.6 | DS=f(RH90, t810, t20) | 0.63 | 2.60 | 2.14 |
| | BOTMOD_9.7 | DS=f(RH90, t10, t1015) | 0.62 | 2.64 | 1.84 |
| | BOTMOD_9.8 | DS=f(RH90, t2025, t10) | 0.59 | 2.76 | 2.29 |
| 8 | BOTMOD_8.1 | DS=f(RH90, t10, t25) | 0.66 | 2.52 | 1.99 |
| | BOTMOD_8.2 | DS=f(RH90, t2025, t10) | 0.50 | 3.04 | 2.18 |
| | BOTMOD_8.3 | DS=f(RH90, t10, t15) | 0.57 | 2.81 | 1.75 |
| | BOTMOD_8.4 | DS=f(RH90, t10, t20) | 0.54 | 2.90 | 2.04 |
| 7 | BOTMOD_7.1 | DS=f(RH90, t10, t25) | 0.54 | 2.77 | 1.58 |
| | BOTMOD_7.2 | DS=f(RH90, t25) | 0.48 | 2.93 | 1.88 |
| 6 | BOTMOD_6.1 | DS=f(RH90, t10, t25) | 0.48 | 2.93 | 1.61 |
| 5 | BOTMOD_5.1 | DS=f(RH90, t25) | 0.54 | 2.76 | 1.71 |

DS represents the mean disease severity expected. RH90, t10, etc., represent the cumulative hours within the specific range. d represents the result of the Durbin-Watson test.

Table 6.2 – Models selected for the validation procedure

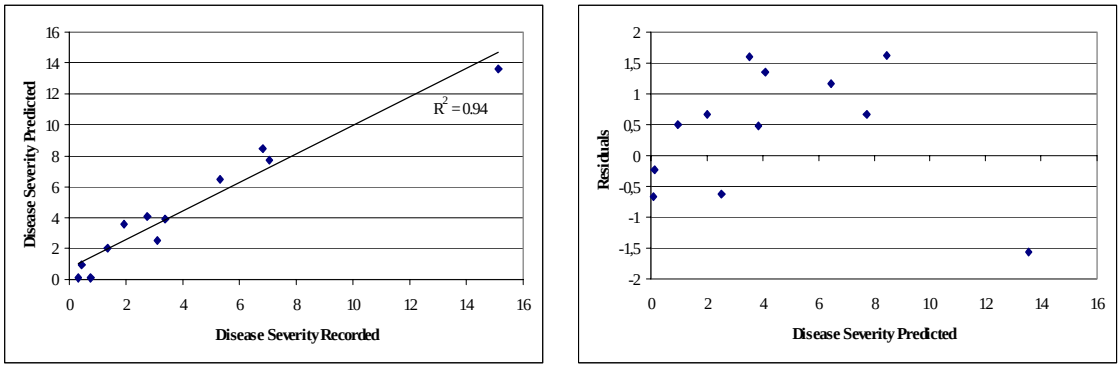
| Model | Parameters | Coefficient | Standard error | $r_a^2$ | *RMSE (see)* |
|---|---|---|---|---|---|
| BOTMOD_17.1 | Constant | -20.161 | 5.414 | 0.90 | 1.36 |
| | RH90 | 0.074 | 0.008 | | |
| | t10 | -0.274 | 0.027 | | |
| | t2025 | 0.224 | 0.076 | | |
| BOTMOD_16.1 | Constant | -13.545 | 5.940 | 0.93 | 1.11 |
| | RH90 | 0.057 | 0.011 | | |
| | RH8590 | -0.078 | 0.037 | | |
| | t10 | -0.303 | 0.024 | | |
| | t2025 | 0.263 | 0.067 | | |
| BOTMOD_16.2 | Constant | -21.755 | 5.258 | 0.91 | 1.29 |
| | RH90 | 0.075 | 0.007 | | |
| | t10 | -0.292 | 0.027 | | |
| | t2025 | 0.272 | 0.077 | | |
| BOTMOD_15.1 | Constant | -15.438 | 5.821 | 0.95 | 0.99 |
| | RH90 | 0.076 | 0.012 | | |
| | RH8590 | -0.052 | 0.039 | | |
| | t10 | -0.344 | 0.024 | | |
| | t2025 | 0.262 | 0.054 | | |
| BOTMOD_15.2 | Constant | -21.684 | 3.608 | 0.94 | 1.02 |
| | RH90 | 0.090 | 0.006 | | |
| | t10 | -0.346 | 0.025 | | |
| | t2025 | 0.282 | 0.053 | | |
| BOTMOD_14.1 | Constant | 6.970 | 5.584 | 0.97 | 0.71 |
| | RH9095 | 0.019 | 0.009 | | |
| | RH8590 | -0.192 | 0.025 | | |
| | RH7075 | -0.090 | 0.020 | | |
| | t810 | -0.392 | 0.036 | | |
| | t1520 | 0.067 | 0.035 | | |
| | t2025 | 0.138 | 0.041 | | |
| BOTMOD_14.2 | Constant | -3.416 | 4.164 | 0.96 | 0.89 |
| | RH90 | 0.059 | 0.010 | | |
| | RH8590 | -0.105 | 0.036 | | |
| | t10 | -0.336 | 0.021 | | |
| | t2025 | 0.169 | 0.039 | | |
| BOTMOD_14.3 | Constant | -13.945 | 2.517 | 0.95 | 0.93 |
| | RH90 | 0.086 | 0.006 | | |
| | t810 | -0.425 | 0.028 | | |
| | t2025 | 0.196 | 0.041 | | |
| BOTMOD_14.4 | Constant | -13.268 | 3.164 | 0.93 | 1.18 |
| | RH90 | 0.083 | 0.007 | | |
| | t10 | -0.321 | 0.027 | | |
| | t2025 | 0.184 | 0.051 | | |
| BOTMOD_14.6 | Constant | 11.107 | 3.714 | 0.92 | 1.22 |
| | RH9095 | 0.039 | 0.010 | | |
| | RH8590 | -0.267 | 0.027 | | |
| | t10 | -0.330 | 0.029 | | |
| | t2025 | 0.143 | 0.053 | | |
| BOTMOD_13.1 | Constant | -26.626 | 8.903 | 0.86 | 1.63 |
| | RH90 | 0.116 | 0.018 | | |
| | t10 | -0.120 | 0.058 | | |
| | t20 | 0.133 | 0.046 | | |
| BOTMOD_13.2 | Constant | 11.831 | 4.507 | 0.90 | 1.37 |
| | RH9095 | 0.044 | 0.012 | | |
| | RH8590 | -0.279 | 0.033 | | |
| | t810 | -0.433 | 0.042 | | |
| | t2025 | 0.123 | 0.060 | | |
| BOTMOD_13.7 | Constant | 10.706 | 4.940 | 0.88 | 1.51 |
| | RH9095 | 0.043 | 0.013 | | |
| | RH8590 | -0.273 | 0.036 | | |
| | t10 | -0.330 | 0.035 | | |
| | t2025 | 0.132 | 0.067 | | |

Table 6.3 – Statistical parameters obtained by comparison of predicted and recorded Disease Severity

| Model | $r_a^2$ | *RMSE* |
|---|---|---|
| BOTMOD_17.1 | 0.59 | 4.06 |
| BOTMOD_16.1 | 0.55 | 4.40 |
| BOTMOD_16.2 | 0.59 | 4.00 |
| BOTMOD_15.1 | 0.55 | 4.72 |
| BOTMOD_15.2 | 0.55 | 4.59 |
| BOTMOD_14.1 | 0.33 | 5.68 |
| BOTMOD_14.2 | 0.33 | 5.68 |
| BOTMOD_14.3 | 0.94 | 1.09 |
| BOTMOD_14.4 | 0.94 | 1.04 |
| BOTMOD_14.6 | 0.41 | 4.67 |
| BOTMOD_13.1 | 0.69 | 2.83 |
| BOTMOD_13.2 | 0.59 | 4.09 |
| BOTMOD_13.7 | 0.38 | 4.43 |

Comparing the results obtained with the selected models in the validation process, it was clear that only the correlations obtained for a period of 14 days before the disease observation gave good predictions and for the 13 day periods the fit between predicted and recorded Disease Severity was reasonable. In both cases Disease Severity is highly correlated with the cumulative hours of relative humidity higher than 90% and temperature lower than 10ºC which is unfavourable for the disease and temperatures between 20 and 25ºC that favours the disease. All the others showed unsatisfactory results when used with the different data during the validation process and did not accurately predict Disease Severity for the conditions which existed. Both models 14.3 and 14.4 represented the recorded data well, and BOTMOD_14.4, was selected as it had the closest *RMSE* values for the estimation and validation processes and also because t10 is a less restrictive independent variable than t810. However, both could be used to predict Disease Severity reasonably well.

Figure 6.1 shows predicted *versus* recorded Disease Severity (a) and the residuals as a function of the predicted Disease Severity (b) obtained by using BOTMOD_14.4. It can be seen that in general, predictions are slightly higher than the observations. However, the majority of the residuals lie between -1 and 1, which is acceptable. Because the available data were not extensive, we believe this model should also be validated with data recorded in commercial greenhouses and with data from other vegetable greenhouse production region, such as Almeria in Spain.




a) b)

Figure 6.1 – Disease Severity predicted *versus* Disease Severity recorded (a) and residuals *versus* Disease Severity predicted (b) obtained using the BOTMOD_14.4

### 6.4.2 Combining the climate model with BOTMOD

The climate model adapted and validated in Chapter 4 was used to generate the air temperature and relative humidity values between the end of April and 9 June 2000. These data were then used to calculate the independent variables necessary to run BOTMOD_14.3 and 14.4 in order to study the integration of the *Botrytis* and climate models. Again, the results obtained with both *Botrytis* models were similar, being slightly better for BOTMOD_14.4 (*RMSE* equal to 2.26 *versus* 2.38 for BOTMOD_14.3). Figure 6.2 shows predicted *versus* recorded Disease Severity obtained by using BOTMOD_14.4 with data predicted by the climate model and with measured climate data, for days of disease observation in May and June 2000.

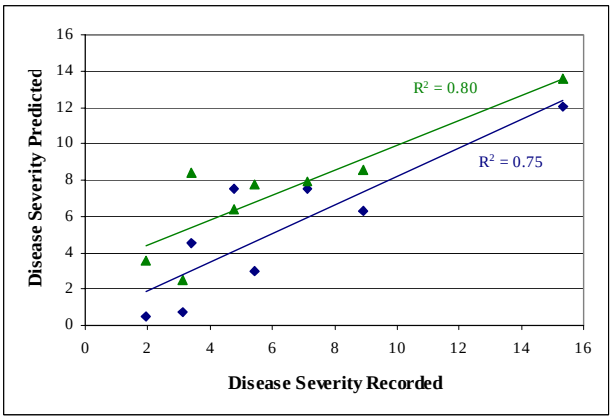



Figure 6.2 - Disease Severity predicted *versus* Disease Severity recorded obtained using the BOTMOD_14.4 with predicted climate data (∀) and with measured climate data (%)

This figure shows there is acceptable agreement between the predicted and recorded Disease Severity values. The performance of the *Botrytis* model with the

predicted climate data is slightly worse than that with the measured data (*RMSE* equal to 2.10). This was expected since the climate model is not perfect, and there is some uncertainty in calculating climate parameters, such as relative humidity, as showed in Chapter 4, which is reflected in the results of the *Botrytis* model. However, 75% of the data fit well and this shows that integration of both models is possible and leads to reasonable results.

### 6.4.3 Recommendations to growers

Tables 6.4 and 6.5 present the mean time (h) per day within several ranges of air temperature and relative humidity during the disease observation periods in 1998 and 2000, respectively. The main objective is to show, for a mean day, the great difference between the duration of periods with relative humidity higher than 90%. In fact, in 1998 a mean day had 4.6 h $day^{-1}$ with RH > 90% while in 2000 it was approximately double at 9.7 h $day^{-1}$. This difference was reflected in the higher Disease Severity in 2000 and also in the high number of chemical treatments. On the other hand, a mean day in 1998 had 7.7 h $day^{-1}$ with relative humidity lower than 70% while in 2000 it was only 2.5 h $day^{-1}$. Also, it can be seen that temperatures lower than 10ºC occurred only during 0.5 and 0.8 h $day^{-1}$ in 1998 and 2000, respectively. In fact, the temperature was higher than 15ºC for approximately 15 h $day^{-1}$ in both years, indicating that temperature was not a limiting factor for disease development. These results enable us to make a qualitative analysis concerning the risk of infection with *B. cinerea* causing grey mould on a tomato crop. This approach can be immediately and directly used by growers, since most of them measure air temperature and relative humidity in their greenhouses:

- HIGH RISK, RH > 90% for more than 9 h per day: prophylactic measures should be used (increase ventilation, cultural measures, chemical or biological sprays);
- MODERATE RISK, RH > 90% for periods between 4 and 9 h per day: increasing ventilation should be enough to reduce relative humidity, depending on the outside conditions;
- LOW RISK, RH > 90% for less than 4 h per day or RH < 90%: no action needed.

Table 6.4 – Mean time (h) per day within several ranges of air temperature and relative humidity between 26 April and 22 June 1998

| Temp. (ºC) / RH (%) | 5 - 10 | 10 - 15 | 15 - 20 | 20 - 25 | 25 - 30 | > 30 |
|---|---|---|---|---|---|---|
| **< 60** | 0.0 | 0.0 | 0.3 | 1.2 | 1.3 | 0.7 |
| **60 – 70** | 0.1 | 1.2 | 0.8 | 1.3 | 0.8 | 0.0 |
| **70 – 80** | 0.0 | 1.2 | 2.1 | 1.1 | 0.2 | 0.0 |
| **80 – 85** | 0.0 | 1.2 | 1.3 | 0.4 | 0.0 | 0.0 |
| **85 – 90** | 0.1 | 2.1 | 1.7 | 0.3 | 0.0 | 0.0 |
| **90 – 95** | 0.1 | 1.6 | 1.4 | 0.0 | 0.0 | 0.0 |
| **95 - 100** | 0.2 | 0.9 | 0.4 | 0.0 | 0.0 | 0.0 |

Table 6.5 – Mean time (h) per day within several ranges of air temperature and relative humidity between 10 April and 16 June 2000

| Temp. (ºC) / RH (%) | 5 - 10 | 10 - 15 | 15 - 20 | 20 - 25 | 25 - 30 | > 30 |
|---|---|---|---|---|---|---|
| **60 – 70** | 0.0 | 0.9 | 0.0 | 0.3 | 0.5 | 0.8 |
| **70 – 80** | 0.0 | 0.7 | 1.1 | 1.6 | 1.8 | 0.6 |
| **80 – 85** | 0.0 | 0.2 | 0.8 | 1.2 | 0.3 | 0.0 |
| **85 – 90** | 0.0 | 1.1 | 1.5 | 0.7 | 0.2 | 0.0 |
| **90 – 95** | 0.5 | 3.4 | 2.2 | 0.3 | 0.2 | 0.0 |
| **95 - 100** | 0.3 | 2.0 | 0.7 | 0.1 | 0.0 | 0.0 |

Figure 6.3 shows a scheme for integrating the greenhouse climate model and the *Botrytis* model (BOTMOD). Predicting the greenhouse internal conditions requires information about the greenhouse-crop characteristics and the outside conditions. Information about the greenhouse characteristics is provided by the manufacturer and information about the crop, can usually be found in the literature or by using crop models as already mentioned. Outside conditions could be available from national weather services, either as recorded data or forecasts for 15 days or more, or could be obtained by growers from data recorded in local meteorological stations.

Based on that information, the climate model will allow the prediction of the greenhouse air temperature and relative humidity over several days. Knowing these parameters, BOTMOD can then be used to predict the expected Disease Severity, which will indicate a risk level for an outbreak of the disease.

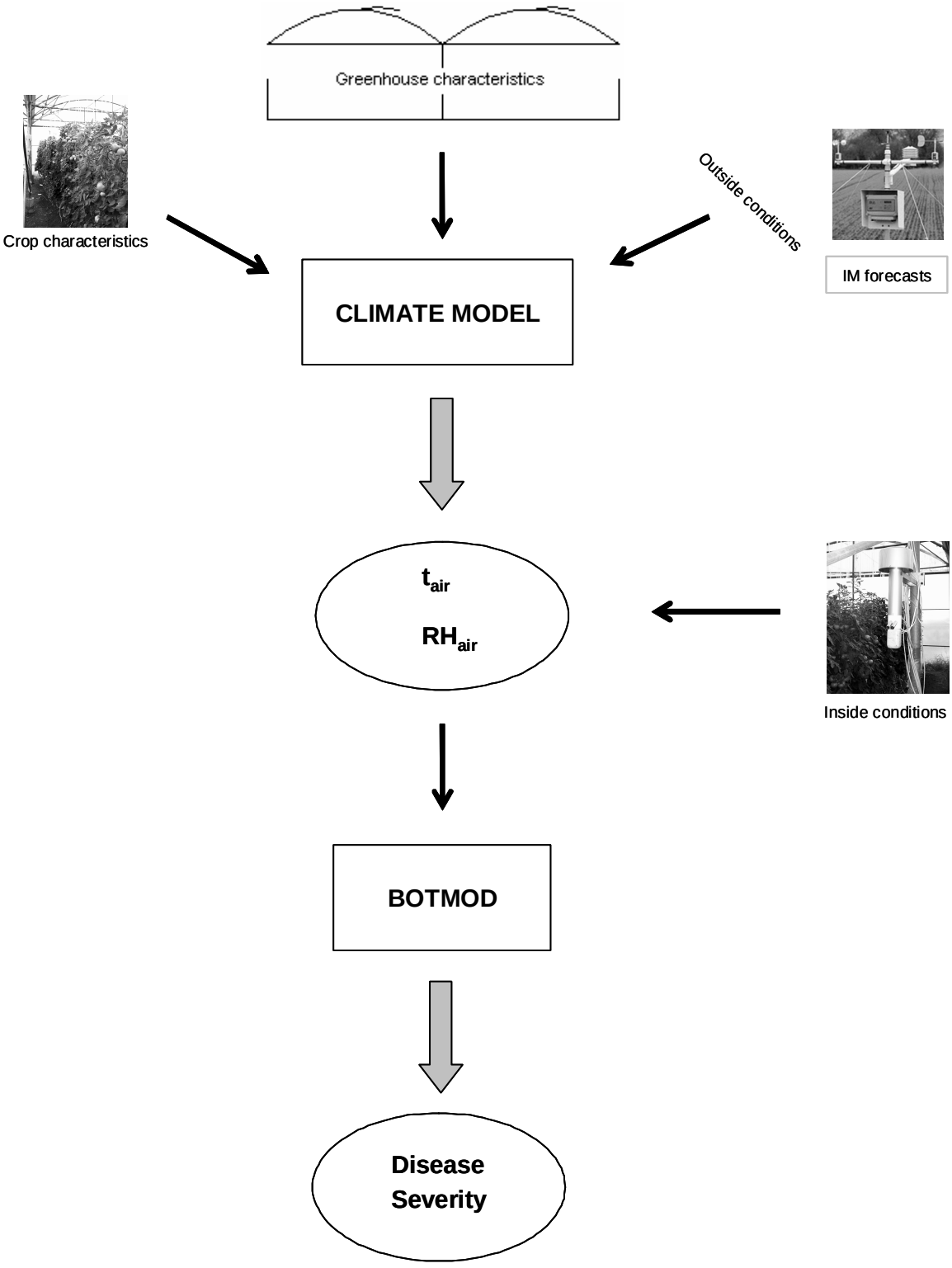



Figure 6.3 – Scheme for integrating the greenhouse climate model and BOTMOD

Using the mean values of Disease Severity obtained during the two years of experiments (1.27 in 1998 and 3.70 in 2000) and the respective actions taken to control the disease, it was possible to estimate the level of risk. The results are presented in

Table 6.6, together with the recommended control actions. Growers need to be convinced on the utility of these recommendations, so it will be necessary to prove that using a decision support system like that proposed will minimise the risk of disease occurrence and will increase profits. The latter will result from reducing the production costs due to less use of chemical sprays and by increasing productivity because there will lower losses caused by the disease, and of course indirectly by the better environment. Growers have to be able to use this approach, which in fact could be one of the application problems! However, growers associations have technicians who will be able to use this and help them to decide on the proper action to minimise losses caused by grey mould disease.

Table 6.6 – Recommendations for *B. cinerea* control based on the expected Mean Disease Severity

| **Disease Severity** | **Risk Level** | **Recommended Actions** |
|---|---|---|
| < 1 | Low | |
| 1 - 2 | Moderate | Increase nocturnal ventilation |
| 2 - 4 | High | Increase nocturnal ventilation<br>Cultural measures<br>Biological or chemical sprays |
| > 4 | Extremely High | Chemical sprays<br>Increase nocturnal ventilation |

Predicting Disease Severity will improve decision making about how and when to act, using all the available control measures such as environmental, cultural, biological and chemical in a way that favourable conditions for disease can be avoided. It has been proved that nocturnal ventilation was able to reduce Disease Severity and if it is possible a priori to know the disease risk level, it will be possible to decide on the increase of greenhouse ventilator area whenever necessary. Of course, this is dependant on the outside conditions and crop stage. At this stage, the latter still relies on the experience of growers.

The possibility of predicting the disease risk level is of great importance, because, even when extremely high risk exists, and chemical use is inevitable, it is important to identify the best time when prophylactic chemical measures should be used to avoid high Disease Severity, since most anti-*botrytis* agents act on spore germination, causing cellular disturbances that inhibit the germination process.

Integration of the climate and *Botrytis* models could provide a useful tool for technicians and advisors as it makes possible to predict the Disease Severity on tomato unheated greenhouses for specific regions by using the relevant weather data. Some more tests combining climate and *Botrytis* models are desirable to reduce uncertainty and to identify possible further adjustments.

## 6.5 Conclusions

A model that allows predicting grey mould severity caused by *B. cinerea* on tomatoes grown in unheated greenhouses was developed and validated. Comparisons between predicted and observed disease data showed good agreement.

Integrating the climate and *Botrytis* models showed it was possible to predict when the conditions would be favourable for *B. cinerea* development and also the likely severity of the expected grey mould outbreak. Knowing this in advance gives growers the opportunity to decide what to do in order to avoid disease favourable conditions. A warning system, defining disease risk level based on Disease Severity was developed and could be a useful tool for technicians, advisors and finally for the growers.

Model generalization is very complicated since many factors influence the climate inside a greenhouse and in consequence the behaviour of crops and pathogens; this justifies the difficulty of developing a single model for a given crop and pathogen. More work is desirable for validating the model developed with data recorded in commercial greenhouses under a wide range of weather conditions.

Most growers follow a chemical treatments calendar based on their experience and also rely on recommendations from the supplier's technicians. Nowadays many commercial greenhouses are equipped with sensors to measure and record, at least, air temperature and relative humidity. With this information and applying simple rules, like those proposed based on the total time per day with relative humidity higher than 90%, growers could reduce the number of chemical sprays, with economical and environmental benefits. This will make it possible to act in time to reverse those conditions, by increasing ventilation or in cases when the risk is too high, by applying preventive fungicides. Other control measures such as cultural (e.g. remove debris from the greenhouse, type of irrigation system) or biological should also be considered. In fact, grey mould caused by *B. cinerea* is not easy to control completely unless several control methods are used and combined in an integrated approach.

# 7. Discussion and conclusions

## 7.1 General discussion

At the beginning of this thesis it was stated that ventilation is the main technique used for environmental control in unheated Mediterranean greenhouses. Also, stated were the negative economic and environmental impacts of grey mould disease caused by *B. cinerea* in greenhouse tomato crops. The main purpose of this research, mentioned in Chapter 1, was to find a sustainable solution to avoid or at least minimise *B. cinerea* infection in unheated tomato greenhouses by using nocturnal ventilation as a way of reducing relative humidity. The ultimate goal is to control the disease, reducing as much as possible the use of chemicals, increasing profit and reducing environmental impact.

An experimental design, described in Chapter 2, was defined in order to reach the stated objectives. The measurements made, results obtained and analyses undertaken that were considered essential to achieve the objectives are described in the four subsequent chapters of this thesis.

In Chapter 3 the greenhouse climate parameters were presented and analysed in order to investigate the effect of nocturnal ventilation on the internal conditions. The results have shown that nocturnal ventilation is an important tool that can be used in unheated greenhouses without lowering the air temperature to give an important reduction of air humidity, which contributes to significantly diminishing the occurrence of *B. cinerea*. In Chapter 4 a dynamic greenhouse climate model was adapted and validated. It can be used to predict the greenhouses climate conditions accurately, enabling it to be used in an integrated system which combines the climate and disease models.

The other aspect of extreme importance in this research was the quantification of the *B. cinerea* occurrence in tomato crops grown in greenhouses with the different ventilation management and no heating. Chapter 5 deals with the results of the disease observations. Disease Severity and Disease Incidence were analysed in order to investigate the influence of the ventilation management on the occurrence of grey mould. It was proved that nocturnal ventilation is a technique which enables the reduction of Disease Severity and Disease Incidence on tomato leaves. These results are even more interesting due to the different weather conditions which occurred in 1998

and 2000. The spring of 2000 was very humid and even so it was possible to significantly reduce the number of lesions caused by this fungus in the nocturnally ventilated greenhouse. Ventilation management can be used as a prophylactic measure, since it reduces the Disease Severity caused by *B. cinerea* on tomato crops grown in unheated greenhouses.

In Chapter 6 a *Botrytis* model (BOTMOD), that allows the prediction of Disease Severity as a function of climate parameters such as air temperature and relative humidity was developed and validated. Comparisons between predicted and observed disease data showed good agreement. The integration of climate and *Botrytis* models permits predicting when the conditions would be favourable for *B. cinerea* development and what would be the expectable grey mould severity.

A warning system, based on the Disease Severity associated with the disease risk levels was developed and could be a useful tool since it gives some recommendations to reverse or to avoid the favourable conditions for disease development. The challenge is to be able to exploit these systems and to provide this information to the final users. It is important that results obtained by the research community should be applied. For that it is necessary that growers, technicians and advisers are convinced of the advantages of new approaches. It is our opinion that this approach should be tested further with data recorded in commercial greenhouses. Another application could be to use weather data from different regions to predict the potential Disease Severity to identify the regions of tomato production which are more susceptible for disease occurrence.

For a more practical and immediate application, disease risk levels were defined as a function of the time duration with RH > 90%. This is a useful tool for growers, since it provides a warning of an increasing disease risk and gives the grower the opportunity to decide what to do in order to avoid disease favourable conditions. This approach would help to reduce the number of chemical sprays, with unquestionable economical and environmental benefits.

In recent years in Europe, society has become increasingly concerned with the environment and a general trend to reduce pesticides has emerged. Consumer demands for safe, healthy and high quality products have increased. Product quality and different production strategies could be important factors for increasing the competitiveness coming with globalization. Grower's education, training and acceptance are of prime importance and can be limiting factors. Researchers and University Extension Services

should be an active partnership in continually developing and providing the recommendations to improve production systems.

This thesis has confirmed the hypothesis that nocturnal ventilation can reduce greenhouse humidity, lowering *B. cinerea* occurrence and in consequence it is possible to reduce the use of chemicals. However, an efficient control of *B. cinerea* disease needs an integrated approach using all available control measures such as environmental control, cultural, biological and sometimes chemical.

## 7.2 Conclusions

1. Nocturnal ventilation is an important technique that can be used in unheated greenhouses to significantly lower the humidity, which can contribute to diminishing some disease attacks, without reducing air temperature;
2. A climate model was adjusted and can be used to predict the greenhouse climate accurately, allowing the development of an integrated system which predicts internal conditions and the outbreak of *B. cinerea*;
3. Nocturnal ventilation is an environmental control technique which can be used in unheated greenhouses to reduce *B. cinerea* severity in tomato leaves;
4. Even in wet weather, nocturnal ventilation provides a significant reduction in the number of lesions caused by *B. cinerea*;
5. Nocturnal ventilation enables a reduction in chemical use, diminishing production costs and environmental impact;
6. Ventilation management is an environmental control technique which can be used as a prophylactic measure;
7. A model that predicts grey mould severity caused by *B. cinerea* on tomatoes grown in unheated greenhouses was developed and shows good performance;
8. Integration of climate and *Botrytis* models is possible and leads to reasonable results. This approach allows predicting when the conditions would be favourable for *B. cinerea* development and what would be the expectable grey mould severity. More tests are desirable with data recorded in commercial greenhouses under a wide range of weather conditions. This approach could be used by technicians and advisers by using specific weather data, to identify regions where it would be more probable that grey mould would occur and what would be the expected severity;

9. Knowing the internal greenhouse conditions (either measured or simulated) an immediate and practical application is to use simple rules, like those based on the total time per day with relative humidity higher than 90%. This will allow the prediction of possible outbreaks of the disease and help to decide on the precautions necessary to prevent, avoid or at least minimise the effects of the disease;
10. A warning system, based on Disease Severity associated with disease risk levels was developed and gives recommendations to help growers to decide whether and how precautions should be taken to avoid *B. cinerea* epidemics.

## 7.3 Contribution of the thesis

This research presents some important steps for climate and *B. cinerea* control in unheated tomato greenhouses, since it has:

1. Provided climate data and disease observations from two seasons of experiments;
2. Modified, adapted and validated a dynamic model to predict the greenhouse climate in unheated greenhouses;
3. Developed and validated a *Botrytis* model (BOTMOD) based on greenhouse data and shown how it can be used in disease management;
4. Integrated the climate and *Botrytis* models in a way that can be used to manage disease;
5. Created a disease risk warning model which is practical and immediately useable by growers.

## 7.4 Recommendations for future work

Arriving at this phase of the thesis we are conscious that some other interesting aspects remain to be studied and future work is desirable. Some suggestions are presented below:

- To use the BOTMOD with data from other climatic conditions (Algarve, West, Almeria, etc.);
- Integration of the climate and *Botrytis* models should be tested further, mainly in commercial greenhouses, before the development of software and

implementation in practice. This will help to establish the accuracy, by validation with other sets of data and identify possible further adjustments. Also, it will permit having the grower's contribution which is important for the implementation and success of any decision support system;

- Practical application of the models by running the climate and *Botrytis* models with weather data from several years and analysing the implications for disease control in different regions;
- To develop a decision support tool that integrates knowledge on the disease, crop and climate. This implies writing a computer programme integrating the climate, crop and *Botrytis* models, that could be used for control purposes;
- To relate internal air properties with the canopy conditions. This could be done using CFD tools which allow simulating conditions inside the greenhouses in different locations;
- It is still necessary to investigate further the complex relations between climate, pathogens and the different plant organs.

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