Analysis of the climate change effect on the greenhouse sector and evaluation of risks

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Abstract

The work attempts to assess the effects of global warming on the efficacy of current greenhouse cooling methods following a methodology previously proved for other agricultural buildings. The cooling potential of four greenhouse cooling techniques (natural ventilation, forced ventilation, fogging and shading) were simulated by computer modelling for five European locations, calculating the greenhouse internal air temperature from measured external climate data. Four 2080s scenarios were analysed in these five locations. They were constructed as a combination of General Circulation Models (Had CM2 and ECHAM4) downscaled for Europe with the HIRHAM and RCA3 regional models and driven by the A2 and B2 socio-economic scenarios. The crop considered as reference was tomato. The results showed that, in locations in southern Europe, adding evaporative cooling methods to ventilation and/or shading will be indispensable. In some areas of northern Europe, natural ventilation will no longer be sufficient, and shading or fogging will also be necessary. The economic consequences will be important, over all in the southern locations where the investment and working costs will be higher and necessary to ensure the crop production.

Key Words: General Circulation Models, downscaling, cooling system, greenhouses

1. INTRODUCTION

In this study, a methodology developed in a previous work (Valiño *et al.*, 2010) is used to evaluate the changes in cooling technologies of greenhouses derived from the different scenarios of global climate change.

In the Fourth Assessment Report (AR4), the Intergovernmental Panel on Climate Change (IPCC, 2008) informed of improved models that enabled best estimates of climate change for different emissions scenarios. These projections of future climate change from numerical models have existed for long, but the PRUDENCE project has provided high resolution change scenarios for Europe at the end of the twenty-first century (Christensen et al., 2007; Olesen et al., 2007, Mínguez et al., 2007). This modelling process involved General Circulation Models (GCM) and the Socio-Economic Emission Scenarios (SRES) described in the AR4. The General Circulation Models are able to predict climate change trends in great areas, and in connection with additional tools (Regional Climate Models, RCMs), information can be downscaled for smaller areas. The PRUDENCE project used this dynamical downscaling method through RCMs, but it is also possible to get high-resolution projections based on statistical downscaling. The stochastic weather generators (WGs) are models which use observed weather local data to simulate synthetic time-series of daily weather that are statistically similar to observed weather in the desired local site. Semenov and Stratonovitch (2010) have released a WG which includes the predictions from different GCMs used in the IPCC AR4 and show another way of using a multi-model ensemble.

Scenarios represent alternative futures in case of climate change. Socio-economic scenarios are defined by the IPCC Special Report on Emission Scenarios (IPCC SRES, 2000), representing the potential socio-economic futures that will determine the level of greenhouse gas emissions to the atmosphere. Each one of the SRES socio-economic scenarios takes a different direction of future developments. The basic emission scenarios (A1, A2, B1, B2) represent storylines about possible world developments in economic growth, population increase, global approaches to sustainability and other sociological, technological and economic factors that could influence greenhouse gas (GHG) emission trends. In the scenario family A, economic development is the priority; while in the scenario family B environmental sustainability considerations are important. For instance, the emission scenario A1B, “contemplates a world with very rapid economic growth, a global population that peaks in the mid 21st century, the rapid introduction of new and more efficient technologies, and a balanced use of fossil and non-fossil energy resources” (IPCC, 2000).

The AR4 states that it is very likely (probability of occurrence >66%) that high temperature extremes and heat wave events will become more frequent in every emission scenario. An increasing frequency of heat waves would have an adverse effect on crop and livestock productivity over and above the impact of changes in mean variables alone (Thornton et. al, 2009; IPCC, 2008). Crop productivity is projected to increase slightly at mid to high latitudes for local mean temperature increases of 1 - 3ºC (depending on the crop), but to decrease at more southerly latitudes (IPCC, 2008). Global warming could have particularly remarkable effects on greenhouse cultivation. The aim of greenhouse cultivation is to prolong optimal growing conditions (perhaps throughout the year), but care must be taken to ensure these conditions are maintained as the external climate strongly affects the greenhouse microclimate and its control.

Ventilation, either mechanical (via exhaust fans) or natural (via wind or buoyancy) is the main method used for removing excess heat, both in southern and northern Europe (Baille, 2001; Särkkä et al., 2006). However, this system is commonly insufficient for maintaining suitable greenhouse internal temperatures - especially in the Mediterranean area. Moreover, the need to install anti-insect screens to prevent the entry of viral diseases generally results in a reduction of ventilation efficiency. Katsoulas et al. (2006) reported the mean value of the normalised air velocity to be 65% lower in a greenhouse with insect screens on the side vent openings than in a greenhouse without these screens. Ventilation systems are therefore commonly used in conjunction with shading and/or evaporative cooling systems.

Shading is achieved by whitening (mainly in the south of Europe) and by placing shade screens inside or outside the greenhouse. Perdigones et al. (2008) reported a natural ventilation plus shading screen strategy to reduce the air temperature by 1.45 ºC (inside minus outside) compared to natural ventilation alone. These shading systems, moreover, have the effect of changing the quantitative and qualitative properties of the light environment. For example, whitening tends to enrich the photosynthetically active radiation (PAR) content of the transmitted light (Kittas et al., 1999), whereas internal aluminised screens strongly reduce it. Nonetheless, tomato quality has been found more dependent on temperature than on the amount of PAR radiation (Riga et al., 2008).

Greenhouse evaporative cooling systems have been developed to provide the desired temperature and humidity conditions for growing crops. These are based on the conversion of sensible heat into latent heat of evaporated water (mechanically supplied) (Arbel et al., 1999). The main evaporative methods used today are sprinkling, pad-and-fan, and fog cooling (fogging). Fogging combined with ventilation has proven to be an effective method for providing a wide range of desired temperature and relative humidity in most months of the year (Arbel et al., 1999; Perdigones et al., 2008). Furthermore, if this system is combined with forced ventilation, the climatic conditions achieved throughout the volume of the greenhouse can be very uniform (Arbel et al., 2003).

The aim of this work was to estimate the adequacy of eight strategies for cooling greenhouses at the present time and in the future frame of the climate change (2080s scenarios). The study was carried out for five European locations: Almeria (Spain), Athens (Greece), Milan (Italy), Stuttgart (Germany), and De Bilt (The Netherlands); using a steady-state balance model. These locations represent the climate range confronting producers of protected crops in Europe. The modelling pretended to assess how the global warming progressively may affect these productive areas.

2. MATERIALS AND METHODS

2.1. Weather data

The locations where the simulations were carried out were: Almeria (36.9º N, 2.4º W and altitude 21 m); Athens (38.0º N, 23.7º E, altitude 107 m); Milan (45.5º N, 9.19º E, altitude 107 m); Stuttgart (48.7º N, 9.2º E, altitude 419 m); and De Bilt (52.1º N, 5.2º E, altitude 2 m). The weather data required by the energy model in greenhouses were the following: the hourly mean temperature, the hourly mean relative humidity, and the hourly mean solar irradiation on a horizontal surface. In this study, monthly time series of average temperature for the period 1961 to 1990 were provided by the PESETA project (Ciscar et al., 2009) whereas monthly time series of relative humidity and solar irradiation were obtained from the European Climate Assessment & Dataset (Klein et al., 2002) and other official climate institutes. Based on these monthly data, the necessary hourly values of temperature, relative humidity and solar radiation were calculated for each hour of an average day of each month, following the models described and validated by García et al. (1998) and with the following assumptions. The daily minimum temperature occurs 1 h before sunrise (for a good adjustment of the curve); the daily maximum temperature occurs 2 h after solar noon; the mean temperature occurs 2 h after sunset; and the temperature profiles from each mentioned point to the next are describe with a sine function (three sine curves for three period each day). The three equations must have common values at their common points. Hourly values for solar radiation were generated from daily means by assuming that solar radiation versus time of day follows a sine function, taking into account the length of the day. Finally, hourly values for relative humidity were generated from daily means by assuming that absolute humidity is constant along the day, so relative humidity in each hour can be calculated with the temperature in each hour and the constant value of absolute humidity.

The whole time slice was used (1961 to 1990) and the output was 24 hours per day, one day per month, 12 months per year, for one average year. These average periods were representative of the base line scenario.

For the 2080s climate projections for each site, four climate scenarios were used in the study (Table 1). The climate projections at the site level were derived from the downscaled projections of the PESETA project (Ciscar et al., 2009). This involved a combination of General Circulation Models (Had CM2 and ECHAM4) downscaled for Europe with the HIRHAM and RCA3 regional models and driven by the A2 and B2 socio-economic scenarios (SRES). In the study the SRES A2 and B2 were considered since they are used by many other studies and they cover a wide range of possibilities, avoiding the extreme non-realistic assumptions of the A1 and B1 scenarios in terms of population growth and economic development. Finally, the monthly time series of average temperature at each site and each scenario were obtained by applying the monthly changes in the downscaled scenario temperature compared to baseline, to the time series of observed temperatures at each site. This procedure has been applied in many agricultural studies to derive projections at the site level (Iglesias et al., 2000; Parry et al., 2004). The humidity ratio and solar irradiation were deemed to be constant despite the temperature rise, comparing the base line with the 2080 scenarios. However, a complete set of calculations were also carried out with an increase of the humidity ratio of 10% in the 2080 scenario, with respect to the base line scenario. The necessary hourly values of an average day of each month were again obtained with the methodology described (García et al., 1998).

The site results agree with Olesen et al. (2007) that found that the variation in simulated agricultural impacts was smaller across scenarios from RCMs nested in a single GCM than it was across different GCMs or across the different emissions scenarios.

2.2 Cooling equipment

The cooling strategies modelled in the study were:

(1) Natural ventilation. High ventilation efficiency with ventilation rate $N = 15\ h^{-1}$.

(2) Natural ventilation (N = 15 h^{-1}) and permanent shading with an unrolled shading screen (24 h) or a whitened cover.

(3) Forced ventilation. One ventilation rate was tested N = 40 h^{-1}.

(4) Forced ventilation and permanent shading, by adding permanent shading to strategy 3.

(5) Natural ventilation and fogging. The above-mentioned (in strategy 1) ventilation rate was combined with fogging (water flow or q = 0.6 L m^{-2} h^{-1}).

(6) Natural ventilation (N = 15 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1}) + permanent shading (24 h).

(7) Forced ventilation and fogging. Fogging (q = 0.6 L m^{-2} h^{-1}) was added to the ventilation situation defined in strategy 3.

(8) Forced ventilation (N = 40 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1}) + permanent shading.

Some of these cooling strategies (1, 2, 5 and 6) had been experimentally tested in a previous work (Perdigones et al., 2008).

Natural ventilation was controlled depending on the outside global solar radiation; thus, the windows were closed at night and open during the day. The forced ventilation was deemed to have an on-off control depending on the outside solar radiation level, with an opening/closing set point of 400 W m^{-2}. The fogging system was assumed to be regulated by an on/off switch set at 25ºC.

2.3. Steady-state balance model

The model used in the present work was the steady state model of Seginer (2002). This incorporates the Penman-Monteith evapotranspiration equation into the standard ventilation design formula. This model takes into account the following energy fluxes (W m^{-2}):

$$\tau S_o = U(T_g - T_o) + \rho c Q \varphi (T_g - T_o) + \frac{\rho \lambda \varphi Q}{B + \rho c \varphi Q}\left(A \tau S_o + Bs(T_g - T_i) + \lambda E_f\right) \quad (1)$$

- Radiation load = τ S_o, where S_o (W m^{-2} [ground]) is the solar radiation flux outside the greenhouse, and τ (dimensionless) is the proportion of the solar radiation transmitted through the cover and used to increase the internal air enthalpy.
- Sensible heat dissipated by convection-conduction through the greenhouse cover = $U (T_g - T_o)$, where U (W m^{-2} ºC^{-1}) is the heat transfer coefficient through the cover, and T_g and T_o are the greenhouse and outside air temperatures respectively (both in ºC).
- Sensible heat dissipated by ventilation = $\rho c Q \varphi (T_g - T_o)$, where ρ (kg[air] m^{-3}) is the air density, c (J kg^{-1} ºC^{-1}) the specific heat of air at constant pressure, and Q (m^3[air] m^{-2}[ground] s^{-1}) is the specific ventilation rate and φ (dimensionless) the air-mixing coefficient as defined by Seginer (2002).
- Latent heat dissipated by ventilation and the evapotranspiration of the crop = $[\rho\lambda\varphi Q/(B+ \rho\lambda\varphi Q)]*[A\tau S_o+Bs(T_g-T_d)]$ (W m^{-2}), where λ (J kg^{-1}) is the latent heat of vaporization of water, B (W kg[air] m^{-2}[ground] kg^{-1}[vapour]) and A (dimensionless) are the radiation coefficient and aerodynamic coefficients in the Penman-Monteith equation, s (kg[vapour] kg^{-1}[air] ºC^{-1}) is the slope of the humidity-ratio saturation curve, and T_d (ºC), the dew-point temperature of the outside air. The remaining variables are the same as described above.
- Latent heat dissipated by the fogging system = $[\rho\lambda\varphi Q/(B+ \rho\lambda\varphi Q)]*[\lambda E_f]$ (W m^{-2}), where E_f is the evaporation rate (kg [vapour] m^{-2} [ground] s^{-1}) of the fogging system.

From expression (1), an explicit equation for T_g (ºC) can be obtained (Seginer, 2002):

$$T_g = \frac{\tau S_o + UT_o + \rho c Q \varphi T_o - \dfrac{\rho \lambda \varphi Q}{B + \rho c \varphi Q}\left(A \tau S_o - BsT_d + \lambda E_f\right)}{U + \rho c Q \varphi + \dfrac{\rho \lambda \varphi Q}{B + \rho c \varphi Q} Bs} \quad (2)$$

2.4. Model coefficients and assumptions

Equation 2 was used to calculate the air temperature T_g (ºC) inside the greenhouse from the available outside weather data. The simulation provided an hourly T_g value for an average day for each month at each location.

The coefficients τ and U used in the model were taken from Perdigones et al. (2008). These values were τ = 0.63 and U = 14.8 W m^{-2} ºC^{-1} when no shading screen was used, and τ = 0.35 and U = 11.8 W m^{-2} ºC^{-1} when one was used. The air mixing ratio was taken as φ = 1 since the greenhouse was deemed to have roof vents and therefore the air inside as completely mixed. The Penman-Monteith coefficients A and B were those quoted by Seginer (2002) following a study by Jolliet (1994) with tomato: A = 0.28 and B = 12 000 W kg[air] m^{-2} kg^{-1}[vapour].

The specific ventilation rates (Q, m^3[air]m^{-2}[ground]s^{-1}) linked to the given ventilation rates (N, h^{-1}) in section 2.2 were calculated considering an average greenhouse height of I = 4 m.

The dew point temperature of the outside air (T_d, ºC) was calculated from the outside relative humidity and the outside air temperature (Singh, 2002).

E_f, the evaporation rate due to the fogging system, was calculated from the flow rate (q, L m^{-2} h^{-1}), with the assumption that all the droplets evaporated before hitting a solid surface and before leaving the greenhouse. However, this evaporation rate is limited by the relative humidity inside the greenhouse. The inside air was considered to have a maximum relative humidity of 90% since higher levels are difficult to reach. This limited the effective E_f for the more humid climates of northern Europe (better reflecting the true conditions experienced in this region). The E_f was taken as the lower of the values provided by following equations:

$$E_f = (W_{90\%} - W_{RHo\%}) \cdot \rho \cdot I \cdot N \frac{1}{3600} \quad (3)$$

$$E_f = q \cdot \frac{1}{3600} \quad (4)$$

where $W_{90\%}$ (kg[vapour] kg^{-1}[air]) is the humidity ratio of the outside air when the relative humidity reaches 90%, and W_{RHo} (kg[vapour] kg^{-1}[air]) the actual humidity ratio of the outside air at the time of calculation.

3. RESULTS AND DISCUSSION

3.1. Weather data

Table 2 shows the main meteorological data for each location in the base line scenario. Modelling was performed for the Mediterranean climate of Almeria (T_o = 19.20 ºC; RH_o = 67.33%) through to the cold and wet climate of Stuttgart (T_o = 8.82 ºC; RH_o = 76.34%).

Modelling for the 2080s involved considering the four climate scenarios described in Material and Methods. Table 3 shows the main meteorological data for each location in the 2080s frame for the four scenarios. The outside global solar irradiance S_o was considered the same at all the scenarios. The RH_o values are lower in Table 3 (2080s scenarios) than in Table 2 (base line scenario) since these were recalculated using the 2080 temperatures and with the assumption that the absolute humidity (or humidity ratio) was constant over time.

3.2. Cooling strategy simulations

Tables 4 and 5 (for the base line frame and the scenarios 2080 respectively) show the results obtained.

The reference crop used in simulations was tomato (*Lycopersicon esculentum* Mill.); its growing months were understood to be those of interest at each location. Thus, in the northern locations (Stuttgart and De Bilt), the model covered the entire year (growth occurs throughout the year), while in southern Europe (Almeria, Athens and Milan), the summer season (June, July and August) was not taken into account since no tomato growth occurs at this time.

The upper threshold temperature for tomato growth has been recorded as 30ºC (Camejo et al., 2005); this value was therefore taken as the boundary temperature to determine whether a strategy was feasible for the cooling of greenhouses. Moreover, it is known that heat stress in crops is not only function of temperature, but duration is other factor to be taken into account (Wahid et al., 2007). In other words, the strategy was considered not feasible when the temperatures over 30ºC lasted more than two hours.

For the baseline frame, Table 4 shows the maximum hourly temperatures for each location obtained with each cooling strategy. The highlighted cells indicate the situations in which the maximum temperature was lower than 30ºC or being higher than 30ºC, they lasted less than two hours. For the two most southern locations Almeria and Athens, the feasible strategies were those that involved fogging. In Almeria, the climate conditions demanded to combine natural ventilation with fogging and shading; in Athens permanent shading was not necessary. In the baseline, results for Milan were more similar to those for the northern locations (Stuttgart and De Bilt), where the natural ventilation was enough to meet the cooling requirements. In fact, the fogging was not activated as the outside temperatures did not exceed the control set-point (25ºC) in the months of crop cultivation. This explains that the maximum values for the no-fogging and fogging strategies were the same in Table 4.

Table 5 shows the results for the mean ± SD of the 4 future scenarios. In Almeria, not even the use of forced ventilation + fogging + shading (strategy 8) appeared to be sufficient to keep the inside conditions below 30ºC. This combination of technologies would work at least in emission scenarios 1 and 2 during the crop cultivation, but in scenarios 3 and 4, September would be a critical month for growing tomato in the greenhouse. In Athens and Milan, it would be necessary to combine natural ventilation and fogging, thus respect to the base line frame, Athens would not invest in any change of technology whereas Milan would have to do it. In De Bilt, the installation of a shading screen would be sufficient to keep the inside conditions; and in Stuttgart the growers should add a fogging system to natural ventilation (Table 5), though in scenarios 3 and 4 there would be problems to meet the cooling needs (mean value 29,91± 0,95 ºC).

It is obvious that these changes imply variations in costs associated with cooling. Growers not only will have to invest in new technologies, but they will have to let them work longer as well. For instance, in the case of Almeria, it will be necessary to implement forced ventilation and to increase the working hours of fogging. The investment cost of the former technology is about 3.1 € m^{-2} (Romero et al., 2002), and the operation cost is mainly due to the electricity consumption. Assuming an electrical power ratio of 3 W m^{-2} for the forced ventilation, and an electricity cost of 0.1 € kWh^{-1} (Valiño et al., 2010), this cost can be calculated with the total working hours, in Almeria up to 1200 h yr^{-1} (0.36 € m^{-2} yr^{-1}). Respect to fogging, the main variation in cost caused by warming would be the water costs, which are higher than electricity costs in this case. In the base line scenario, the fogging system was working for 480 h yr^{-1} whereas in the future this data was increased in 300 – 1170 h yr^{-1} depending on the scenario (an increase from 62.5% to 243.8%). With these increases and the fogging rate (0.6 L h^{-1} m^{-2}) is possible to calculate the water consumption in the future, ranging from 468 to 990 L m^{-2} yr^{-1}. In Athens the fogging system would have to work longer as well, thus respect to the base line, the increase would range from 275% to 375%. Moreover, in Milan, the investment cost of fogging (3 € m^{-2}, Valiño et al., 2010) would have to be taken into account as this technology would be implemented from scratch; its working hours ranged from 240 to 570 h yr^{-1}. Figure 1 shows the increase of the water consumption from the base line to the future scenarios for these southern locations.

A complete set of calculations was carried out with an increase in the humidity ratio of 10% in the 2080s scenarios, with respect to the baseline scenario. In Table 6, the results for De Bilt and Almeria are shown. This batch of simulations did not show any change affecting the maximum temperatures or cooling technologies with respect to the rest of the simulations, performed with the assumption of a constant humidity ratio (Table 5). Despite of increasing the relative humidity, the evaporative system (fogging) was not able to evaporate water enough to achieve the upper threshold $W_{90\%}$ and the results were the same as in the constant humidity scenarios.

Table 7 summarizes the changes in cooling technologies that the growers would assume by the 2080s so as they could keep the cooling requirements of their greenhouses. In southern locations, Almeria, Athens and Milan, departing from different levels of cooling equipment in the baseline frame, they will have to run a combination of natural or forced ventilation with fogging and shading. In the case of Almeria this combination will not meet wholly the cooling needs inside the greenhouse in every future scenario. The greenhouses will work in suboptimal conditions in the summer months, but that situation will not be as different as it is at the present time. At least in the south of Spain, natural ventilation is the main technique to evacuate the excess of heat, and temperatures usually reach unacceptable levels for the crop. However, the situation of these sub-optimal greenhouses will get worse in the 2080s, with socio-economic consequences: growers will have to install cooling facilities, change the period of crop production or take down the greenhouses (Fig. 2).

The northern locations Stuttgart and De Bilt will face up to a different situation. The viability of their greenhouses will depend on implementing shading in the case of De Bilt, or fogging in Stuttgart. Natural ventilation will be enough most part of the year, and the active cooling will be only needed to extend the period of crop production throughout the summer months. Though changes in northern areas would be less critical than in southern Europe, shading or whitening would have direct consequences on the crop development, as in the North of Europe the levels of solar radiation are low and decreasing it implies decreasing production.

The present study was carried out with tomato, but other conventional protected crops in the greenhouse sector could have to cope with the same situation, depending on their upper threshold temperature (pepper, 40ºC; cucumber, 35ºC; eggplant, 50ºC; as referenced in Serrano, 2005). The same methodology described in this article can be applied to other given vegetable species.

4. CONCLUSIONS

This works makes use of a methodology previously developed to evaluate changes in cooling technologies of agricultural buildings, derived from different scenarios of global climate change. Four 2080 scenarios were analysed for 5 European locations and 8 cooling strategies combining natural and forced ventilation, fogging and shading.

Deep changes in cooling technologies were estimated necessary in the southern locations for the 2080s scenarios respect to the baseline frame (1960-1990). Natural ventilation resulted insufficient and growers should invest in forced ventilation, fogging and shading; depending on the future scenario, it could happen that the combination of these cooling techniques will not guarantee suitable crop conditions at the present cultivation periods. The increase in the water consumption due to the implement of new fogging systems or the longer working hours of them could be calculated with the methodology described: in Almeria for instance, the water demand would increase from 288 L m^{-2} yr^{-1} up to 468 – 990 L m^{-2} yr^{-1} depending on the future scenario. The increasing temperatures will force progressively to change the period of crop production or take down the greenhouses.

In northern Europe, results indicated slight changes to be made. De Bilt would meet its requirements adding a shading screen to natural ventilation; and in Stuttgart, greenhouses should invest in fogging to face global warming successfully.

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Tables

Table 1. Summary of the four climate scenarios used in the study.

n.	Scenario	Time frame	Driving Socio-economic scenario SRES	General Circulation Model GCM	Regional climate models	Average CO_2 ppmv	Change in mean temperature averaged in Europe (ºC)
1	HadCM3 A2/ DMI/HIRHAM 2080s	2071-2100	A2	HadCM3	DMI/HIRHAM	709	3.1
2	HadCM3 B2/ DMI/HIRHAM 2080s	2071-2100	B2	HadCM3	DMI/HIRHAM	561	2.7
3	ECHAM4/OPYC3 A2/SMHI/RCA3 2080s	2071-2100	A2	ECHAM4	SMHI/RCA3	709	3.9
4	ECHAM4/OPYC3 B2/SMHI/RCA3 2080s	2071-2100	B2	ECHAM4	SMHI/RCA3	561	3.3

Table 2. Yearly mean temperature (T_o, ºC), yearly mean relative humidity (RH_o, %) and yearly mean global solar irradiation (S_o, W m^{-2}) for the different study locations (base line 1961-1990).

Location	T_o , ºC	RH_o, %	S_o, W m^{-2}
Almeria (ES)	19.20	67.33	186.84
Athens (GR)	17.80	65.19	166.92
Milan (IT)	12.21	76.83	148.09
Stuttgart (DE)	8.82	76.34	122.67
De Bilt (NL)	9.29	80.99	117.86

Table 3. Estimated yearly mean temperature (T_o, ºC), yearly mean relative humidity (RH_o, %) and yearly mean global solar irradiation (S_o, W m^{-2}) for the study locations and every future scenario (2080s).

Location	*Scenario 1*		*Scenario 2*		*Scenario 3*		*Scenario 4*		$S_{o,}$ W m^{-2}
	T_o , ºC	RH_o, %	T_o , ºC	RH_o, %	T_o , ºC	RH_o, %	T_o , ºC	RH_o, %	
Almeria (ES)	21.29	58.89	20.69	61.17	24.01	50.29	23.14	52.87	186.84
Athens (GR)	22.08	51.44	20.61	56.22	22.12	51.40	21.14	54.33	166.92
Milan (IT)	16.24	60.68	14.65	67.21	18.40	53.61	16.77	58.85	148.09
Stuttgart (DE)	12.47	60.60	11.08	66.56	15.04	51.83	13.33	57.34	122.67
De Bilt (NL)	13.75	61.51	12.57	65.87	14.06	59.80	12.89	64.40	117.86

Table 4. Feasibility of the current techniques in the base line frame (1960-1990). The temperatures (ºC) in the table are the maximum of values for every month calculated by modelling. The highlighted cells show when the different cooling strategies are feasible for each location.

Location	Strategies[a], Baseline 1960-1990							
	1	2	3	4	5	6	7	8
Almeria (ES)	36.26	34.85	32.72	31.96	31.96	30.40	27.88	27.42
Athens (GR)	34.87	33.47	31.30	30.54	30,57	29,09	28.44	27.58
Milan (IT)	29,61	28,48	26,82	26,21	29,61	28,48	26,82	26,21
Stuttgart (DE)	28.36	27.22	25.47	24.83	28.36	27.22	25.47	24.83
De Bilt (NL)	26.68	25.51	23.60	22.96	26.68	25.51	23.60	22.96

[a] Cooling strategies: 1. Natural ventilation (N = 15 h^{-1}); 2 Natural ventilation (N = 15 h^{-1}) + shading; 3. Forced ventilation (N = 40 h^{-1}); 4. Forced ventilation (N = 40 h^{-1}) + shading; 5. Natural ventilation (N = 15 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1}); 6. Natural ventilation (N = 15 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1}) + permanent shading; 7. Forced ventilation (N = 40 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1}); 8. Forced ventilation (N = 40 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1}) + permanent shading.

Table 5. Feasibility of the current techniques for the future scenarios. The temperatures (ºC) in the table are the mean values and SD of maximum for the four scenarios in the 2080s. The highlighted cells show when the different cooling strategies are feasible for each location.

Location		Strategies[a], 2080s							
		1	2	3	4	5	6	7	8
Almeria (ES)	Mean	39.63	38.21	36.28	35.52	32.52	31.25	31.10	31.03
	SD	± 2.29	± 2.27	± 2.43	± 2.42	± 0.57	± 0.69	± 2.47	± 2.46
Athens (GR)	Mean	38.72	36.45	35.34	33.68	30.64	29.41	30.14	29.41
	SD	± 0.60	± 2.05	± 0.63	± 2.16	± 0.32	± 0.27	± 0.64	± 0.64
Milan (IT)	Mean	34.64	33.49	32.04	31.42	29.74	28.58	27.34	27.10
	SD	± 1.23	± 1.22	± 1.29	± 1.28	± 0.45	± 0.38	± 0.61	± 0.78
Stuttgart (DE)	Mean	36.03	34.89	33.51	32.89	29.91	29.23	29.87	29.23
	SD	± 2.66	± 2.64	± 2.80	± 2.79	± 0.95	± 1.23	± 2.58	± 2.60
De Bilt (NL)	Mean	31.00	28.24	28.04	25.77	30.20	28.24	27.31	25.77
	SD	± 1.51	± 1.96	± 1.56	± 2.02	± 0.78	± 0.75	± 0.73	± 0.71

[a] Cooling strategies: 1. Natural ventilation (N = 15 h^{-1}); 2. Natural ventilation (N = 15 h^{-1}) + shading; 3. Forced ventilation (N = 40 h^{-1}); 4. Forced ventilation (N = 40 h^{-1}) + shading; 5. Natural ventilation (N = 15 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1}); 6. Natural ventilation (N = 15 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1}) + permanent shading; 7. Forced ventilation (N = 40 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1}); 8. Forced ventilation (N = 40 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1}) + permanent shading.

Table 6. Results of simulations considering an increase of the humidity ratio of 10%: yearly mean and standard deviation (SD) of outside air temperature (T_o, ºC), yearly mean and SD of outside relative humidity (RH_o, %); mean and SD of the mean temperatures resulting of the four scenarios modelling (2080s).

Locations				Strategies[a], temperature, ºC			
		To, ºC	RHo, %	5	6	7	8
Almeria (ES)	Mean	22.28	61.29	32.52	31.25	31.10	31.03
	SD	± 1.55	± 5.57	0.57	0.69	2.47	2.46
De Bilt (NL)	Mean	12.71	71.88	30.25	29.11	27.33	26.69
	SD	± 1.13	± 5.33	± 0.78	± 0.75	± 0.73	± 0.71

[a] Cooling strategies: 5. Natural ventilation (N = 15 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1}); 6. Natural ventilation (N = 15 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1}) + permanent shading; 7. Forced ventilation (N = 40 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1}); 8. Forced ventilation (N = 40 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1}) + permanent shading.

Table 7**.** Most suitable cooling strategies for each location in the base line scenario and the future scenarios (2080s).

Locations	Recommended cooling strategy	
	Baseline 1961-1990	2080s
Almeria (ES)	(6) Natural ventilation (N = 15 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1})+shading	(8) Forced ventilation (N = 40 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1}) + shading
Athens (GR)	(5) Natural ventilation (N = 15 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1})	(5) Natural ventilation (N = 15 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1})
Milan (IT)	(1) Natural ventilation (N = 15 h^{-1})	(5) Natural ventilation (N = 15 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1})
De Bilt (NL)	(1) Natural ventilation, N = 15 h^{-1}	(2) Natural ventilation (N = 15 h^{-1}) + shading
Stuttgart (DE)	(1) Natural ventilation, N = 15 h^{-1}	(5) Natural ventilation (N = 15 h^{-1}) + fogging (q = 0.6 L m^{-2} h^{-1})

Figures

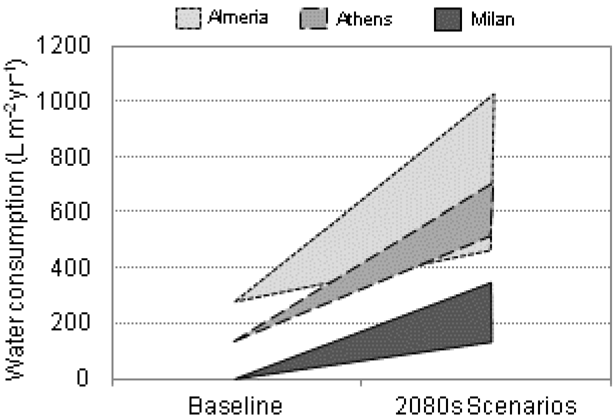

Figure 1. Water consumption (L m^{-2} yr^{-1}) in the four studied scenarios from the baseline up to the 2080s scenarios and for the three southern European locations.

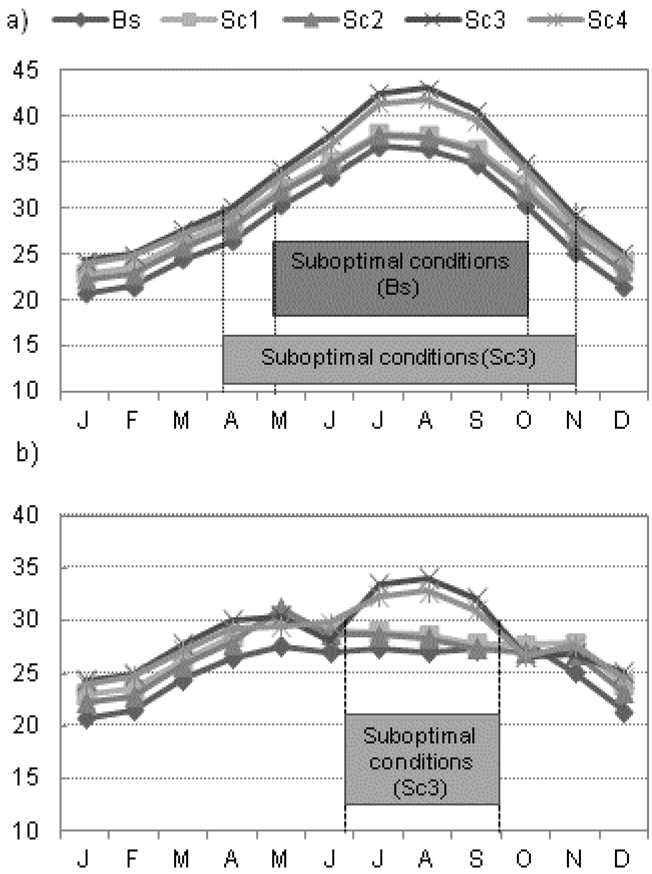

Figure 2. Crop cycle limits. The width of the bands cover the span of the year when the inside conditions of the greenhouse would not be suitable for the tomato cultivation. Monthly maximum temperatures are shown for: a) Strategy 2, natural ventilation and permanent shading; and b) Strategy 6, natural ventilation, fogging and permanent shading. This last strategy resulted effective for the base line throughout the year, thus no suboptimal conditions band appears in the figure.